平成 27 年 2 月修士論文要旨

（東京大学大学院　新領域創成科学研究科　海洋技術環境学専攻）

水底下の生物計測を目的とする三次元音響コアリングシステムの開発

Development of 3-D acoustic coring system for measurement of creatures living in sediment

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1. Background

Cristaria plicata is one kind of bivalves which belong to the Mollusca. They are always living in sand and mud substrates in ponds, lakes and rivers of plains. Cristaria plicatas usually hide most part of their bodies into the lake sediment and are feeding on the straining suspended microorganisms and organics in the sediment, some biologists believe that they are filtering and purifying the water [1-3].

For the time being, intensive biologic researches targeting on the specific creatures living in lake sediment are still scarce. And sampling methods are still the main measurement tools. There are some problems about these method: a) It takes too much labor force and time, b) It leaves damage to the sampling sites.

Taking into consideration of the fact that optical sensors is difficult to be used to measure in the turbid water and sediment, we have concluded that we need to develop 3-D acoustic coring system with an appropriate frequency sensor to make the lake sediment creature measurement feasible and convenient.

2. Objective

My specific research objectives are: 1) Build automatic 3-D acoustic coring measurement system to measure Cristaria plicatas efficiently, 2) Design and make acoustic lens to focus sound waves to a relatively small spot so that we could have a higher horizontal resolution, 3) Analyze measurement experiment's raw signal data and reconstruct 3-D acoustic images of lake sediment.

3. Experiment system

3.1. 3-D acoustic coring system

3.1.1. System configuration

As Fig. 3.1.1 shows, we have built the 3-D acoustic coring system with 3 units, acoustic unit, control unit and 3-D view & image process unit. In the acoustic unit, we have used 1 channel transmitter (Honda Electronic, Aiti prefecture, Japan) and 8 channel receivers (TC-4013-4; Teledyne Reson, Slangerup, Denmark). In the control unit, we have used Labview control program, DAQ (NI USB-6356; National Instruments, Texas, USA), and X and Y axis motors. In the 3-D view & image process unit we have signal data analyzer and image processor.

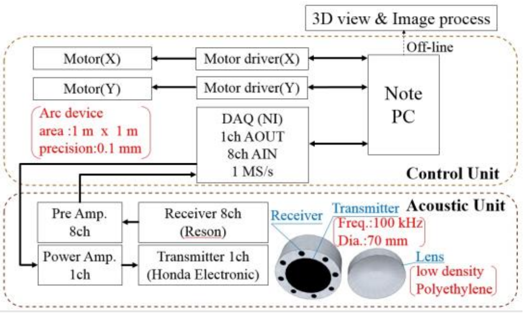

Fig. 3.1.1 System configuration

3.1.2. Data processing

The data process methods are showed as in Fig. 3.1.2, I extract envelope curve of signal and focus the 8 channel's data on center line (vertical direction), by making full use of the correlation process adjustment, then I reconstruct the 3-D images with OpenGl [4-5].

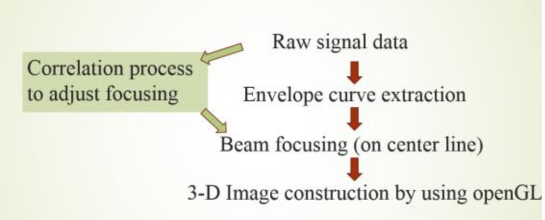

Fig. 3.1.2 Data processing

3.1.3. Field experiment

The purpose of building 3-D acoustic coring system is to measure the creatures living under the lake sediment, so we arranged the field measurement experiment to test the system. Field experiment's site is Lake Izunuma in Miyagi prefecture, the experiment was held in Nov. 20~21, 2014. We have put the measurement object, Cristaria plicata into the experiment site's lake sediment in advance, then we have moved and fixed measurement system flame onto the sediment surface of the experiment site. We have made movement step as 1 cm and measured an area with a width of 85 cm and a length of 90 cm.

3.2. Acoustic lens

3.2.1. Theoretical acoustic lens design

We use refraction principle and Snell's law to design acoustic lens. If there is an acoustic lens, and it can focus the sound waves into one point, which is the focus point, then the transmission time from the surface of the transmitter to the focus point should be an instant figure, as Fig. 3.2.1 and equation below shows.

$$\frac{z}{c_0}+\frac{\sqrt{(y)^2+(L-z)^2}}{c}=\frac{b}{c_0}+\frac{L-b}{c} \quad (1)$$

If we set different z coordinates with very small interval into the equation above, and substitute the given range parameter L into it, we could get a series y coordinates of points on the designed lens surface. Then, we use the reversibility calculation of sound wave to confirm the coordinates of y axis, and we can draw the lens surface line by connecting the points with straight lines [6-10].

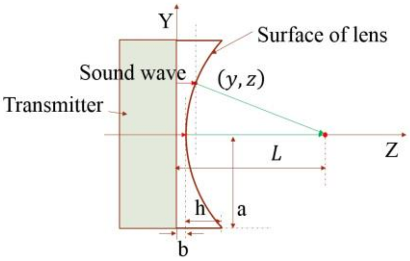

Fig. 3.2.1 Theoretical lens design image

Table 3.2.2 Symbols being used

Symbol	**Unit**	**Significance**
P	Pa	Sound pressure [fluid case]
t	s	Time
Δt	s	Time step of simulation
y, z	m	Coordinates of Y and Z axis
c_0	m/s	Sound velocity in lens
c	m/s	Sound velocity in freshwater
ρ	kg/m^3	Density of fresh water
$ρ_0$	kg/m^3	Density of fresh acoustic lens
V_y, V_z	m/s	Particle velocity on x, y and z direction
Δ, Δy, Δz	m	Grid width

3.2.2. FDTD sound pressure simulation

In order to check the acoustic lens design and learn the sound pressure on every coordinates in the sound field at different times, I have chosen the FDTD (Finite-difference time-domain) method to calculate and simulate sound pressure over sound field.

I have used wave equation, particle velocity equations, and Taylor series to deduce the final FDTD equations to write simulation code. All these equations are expressed on Y-Z plane.

Wave equation: $\frac{\partial P}{\partial t}=-c^2\rho\left(\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z}\right)$ (2) Particle velocity equations: $\frac{\partial P}{\partial y}=-\rho\frac{\partial V_y}{\partial t}$ $\frac{\partial P}{\partial z}=-\rho\frac{\partial V_z}{\partial t}$ (3)

If we substitute the wave equation into the difference equation, we can get the following equation:

$$P(p,q,(s+1)\Delta t)=P(p,q,s\Delta t)-\frac{c^2\rho\Delta t}{\Delta}\Big(v_y(p+1,q,s)-v_y(p,q,s)+v_z(p,q+1,s)-v_z(p,q,s)\Big) \quad (4)$$

Notice that the calculations are interleaved in both space and time. We can use this equation to calculate the sound pressure of s+1 time (the new value), by using the sound pressure value of s time (the most recent value), and particle velocity values of s time. This is the fundamental paradigm of FDTD method. Use the almost same derivation process as expressed above, we can get the final FDTD equations for the calculation and simulation of stress and particle velocities in solid [11-14].

3.2.3. Measurement of sound pressure distribution

After we made the designed acoustic lens, I have arranged the evaluation experiment to test the performance of it by checking the sound pressure distribution of sound field with and without lens. I have put signal receiver into the water tank and fixed lens to bottom surface of transmitter, by taking advantage of the 3-D acoustic coring measurement system, I could control the transmitter to move on X and Y direction and measured sound pressure.

3.2.4. Measurement of horizontal resolution

In order to test the performance of acoustic lens in real measurement experiment, I have arranged measurement experiment to detect concrete in water. I have put the concrete block into the water tank, and measured the size of it using measurement system with and without acoustic lens. Then I compare the difference of measurement results with images I build. I setted the movement step as 5 mm and measured an area with a width of 30 mm, and a length of 560 mm.

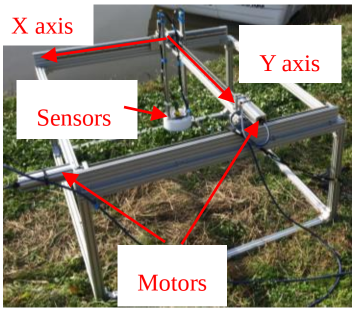

Fig. 4.1.1 3-D acoustic coring system image

4. Results and discussion

4.1. 3-D acoustic coring system

4.1.1. System configuration

As introduced in chapter 3, we have completed building of the 3-D acoustic coring system, Fig. 4.1.1 shows the image of system, including system aluminum frame, sensors (transmitter and receivers), and motors. Because this measurement system can be automatically controlled by PC, it is convenient for measurement and we could set different movement step on X and Y axis to satisfy our measurement accuracy demand. And because we fixed the system frame onto sediment surface, this avoids bringing errors form moving and shaking. Also, we could re-measure the lake sediment over and over again at the same site to see the situation changes under sediment.

4.1.2. Field experiment

By using the data process introduced in chapter 3, I have completed the process of translating the sound wave signal into the 3-D image. Fig. 4.1.2 shows the whole picture of 3-D images and Cristaria plicata under lake sediment. Brightness means the reflection signal's strength. As we can see, the sediment layer can be seen clearly. The lake sediment roughly has 2 layers, first layer is soft and low density, second layer is harder and its density is higher. We can also take some layers out from the complete 3-D image so that we can take a close look at the objects on inner sediment layer. Picture on the right is a Cristaria plicata underneath the lake sediment surface. This Cristaria plicata is the one I have put into the lake sediment, and the measurement experiment result proves that our 3-D acoustic coring system can not only measure objects near surface of lake sediment, but also Cristaria plicata hiding deep into the lake sediment. And the measured size is 5 cm × 11 cm, similar to the real size (5 cm × 8 cm).

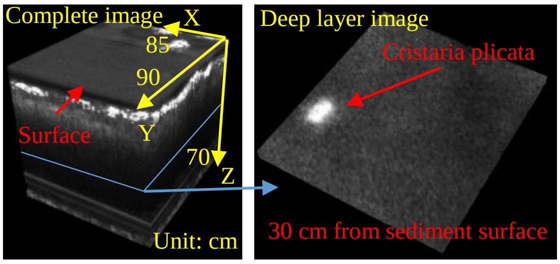

Fig. 4.1.2 3-D image of lake sediment and objects

4.2. Acoustic lens

4.2.1. FDTD sound pressure simulation

Through simulating the sound pressure in the designed sound fields, we have obtained the sound pressure data, which include both water area and acoustic lens area. Fig. 4.2.1 shows the vertical view of sound pressure distribution over the simulation field without and with lens. As we can see, sound waves is emitting widely in the 'without lens' mode, and in the 'with lens' mode, acoustic lens has focused the sound waves to relatively small spot and the spot diameter is very narrow and changing slowly with the increasing of Z coordinate. Compare to the simulation data without lens, we concluded that using lens will give our 3-D acoustic coring system a better horizontal resolution.

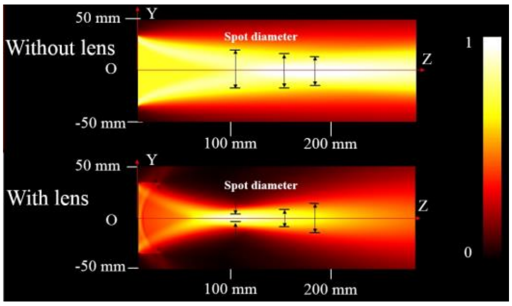

Fig. 4.2.1 Sound pressure distribution (simulation)

In our simulation, we used one pulse signal input with the maximum of 1 Pa, which is ideal condition to simulate. The real input signal of our transmitter has more than 3 periods and has reverberation behind the normal signal waves. And transmitted signal's frequency is not perfectly matching 100 KHz all the time. These factors will bring us some errors and difference between simulation situation and real situation.

4.2.2. Measurement of sound pressure distribution

After we made the acoustic lens, we evaluated lens's performance by checking spot diameters on different positions. I have measured the sound pressure distribution in the sound filed without and with acoustic lens fixing on the bottom surface of transmitter. After obtained the signal data, I have drawn the sound pressure distribution figures, showed in Fig. 4.2.2.1. As we can see in the figures, compare to the sound pressure distribution without acoustic lens, sound pressure value in "with lens mode" is increasing and dropping more quickly. And the sound pressure maximum is actually higher.

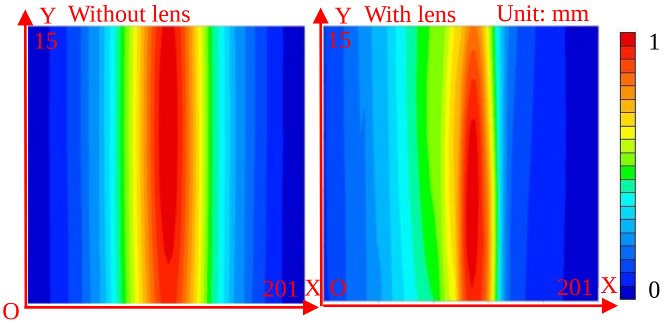

Fig. 4.2.2.1 Sound pressure distribution (experiment)

I have also compared and drawn the comparison figures of sound pressure distribution data between simulation and experiment to validate the whole design and simulation process, showed in Fig. 4.2.2.2. As we can see, the experiment data is mainly similar to the simulation results. This means our acoustic lens design and simulation process are effective and worked out well.

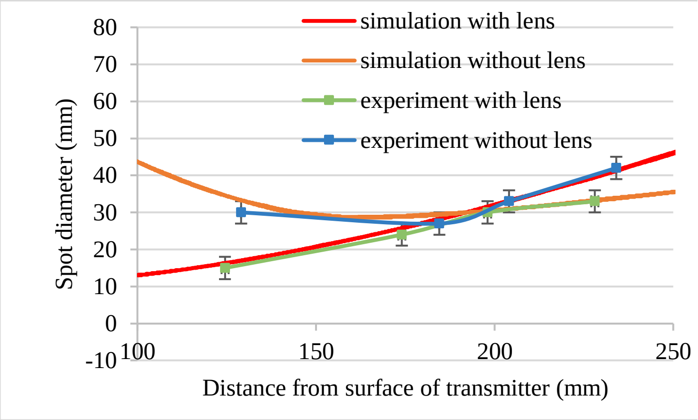

Fig. 4.2.2.2 Comparison of spot diameter variation

And by checking the experiment data and simulation data, we have found that acoustic lens did make the spot diameter of sound filed narrower, and it made the horizontal resolution of our measurement system better. In the case of errors, there are dispersion errors in FDTD simulation method, and there are some errors in the distance between transmitter surface and receiver (experiment error), these may make the simulation spot diameter line deviate from the experiment line somehow.

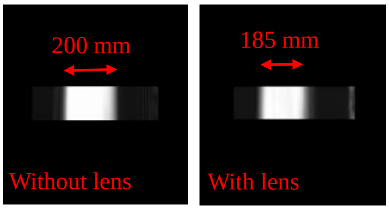

Fig. 4.2.3 Comparison of measurement resolution

4.2.3. Measurement of horizontal resolution

By using the same data process as introduced in chapter 3, I have processed the signal data from the water tank experiments (without and with lens). In order to compare the difference of images between "without lens mode" and "with lens mode", I have made the top views of concrete, as shows in Fig. 4.2.3, We can tell the difference by our eyes that concrete in "with lens mode" image is narrower and it is closer to the real size, which is 18 cm. And I calculated and compared concrete measurement resolution between 2 modes by using -6-dB standard. We obtained the measured sizes of concrete block are 200 mm and 185 mm, this means, by using acoustic lens, we can detect the objects more precisely.

5. Summary

5.1. 3-D acoustic coring system

The 3-D acoustic coring system have been completely built and can be applied to do many kinds of measurement experiment conveniently. According to the measurement resolution requirement, we can adjust the sensors movement step and measurement area. The measurement time is depending on the measurement area's size and the movement step.

5.2. Acoustic lens

We have done sound pressure measurement and horizontal resolution measurement experiment with acoustic lens, the results show that, acoustic lens is a low-cost and convenient method to improve resolution of acoustic measurement system.

6. Reference

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