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Automatic non-destructive three-dimensional acoustic coring system for *in situ* detection of aquatic plant root under the water bottom

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ABSTRACT

Digging is necessary to detect plant roots under the water bottom. However, such detection is affected by the transparency of water and the working skills of divers, usually requires considerable time for high-resolution sampling, and always damages the survey site. We developed a new automatic non-destructive acoustic measurement system that visualizes the space under the water bottom, and tested the system in the *in situ* detection of natural plant roots. The system mainly comprises a two-dimensional waterproof stage controlling unit and acoustic measurement unit. The stage unit was electrically controlled through a notebook personal computer, and the space under the water bottom was scanned in a two-dimensional plane with the stage unit moving in steps of 0.01 m (±0.0001 m). We confirmed a natural plant root with diameter of 0.025–0.030 m in the reconstructed three-dimensional acoustic image. The plant root was at a depth of about 0.54 m and the propagation speed of the wave between the bottom surface and plant root was estimated to be 1574 m/s. This measurement system for plant root detection will be useful for the non-destructive assessment of the status of the space under the water bottom.

1. Introduction

The lotus plant (*Nelumbo nucifera* Gaertn.) is an aquatic emergent angiosperm that is distributed in wetlands from Iran to Japan and from China to Queensland, and is now increasingly being managed [1]. In Japan, the lotus is widely distributed in Japanese eutrophic waters that usually have low transparency [2]. A large proportion of Lake Izunuma has been dominated by lotus, and the area of the lake covered by lotus has increased rapidly since 2006, according to information obtained from aerial photography: 23% coverage in 2006 and 44% coverage in 2008 [3]. The lake was registered as a wetland under the Ramsar Convention in 1985, and therefore, there is a great need to conserve the biodiversity at the lake. However, the

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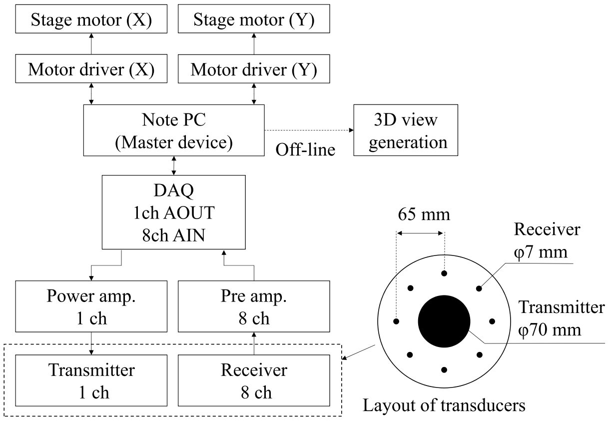

Fig. 1. Block diagram of the measurement system and illustration of the layout of transducers.

rapid increase in lotus coverage has ecological effects on other aquatic plants owing to the light interception of the plant's large leaves. This interception also reduces the quality of water. Hence, it is necessary to understand the lotus distribution to conserve the water environment at the lake. However, the lotus plant usually grows by vegetative reproduction of the lotus root under the water bottom, and the real situation of the lotus distribution is not clear unless the lotus root is dug up. In addition, digging in water requires huge effort and always damages the survey site. It is thus impossible to monitor the temporal change of the same individual. Therefore, an efficient and non-destructive survey method of detecting and monitoring the lotus root in the *in situ* situation is required.

Acoustic systems, such as the sub-bottom profiler system, are used for the detection of buried objects under the water bottom [4–6]. Several types of sub-bottom profiler systems are used for the survey: continuous wave pulse [4], chirp signal [5] and parametric [6]. In the case of continuous wave pulse and chirp signal types, a theoretical horizontal resolution is 0.27–1.37 m in water depth of 1.0–25 m at 10 kHz using the Frenel zone criterion. Therefore, meter-sized objects, such as pipeline [4] and wooden hulls [5], are detectable. The parametric sub-bottom profiler SES-2000® has high horizontal resolution of 0.06 m, in water depth of 1.0 m, with a beam width of 3.6° at 100 kHz fundamental frequency, which makes pipeline and other meter-sized objects detectable [6]. In addition, the profiler is also used for the survey of thin fluid mud and small dunes [7]. In most cases, the sub-bottom profiler systems are mounted on the survey ship and use a single beam, thus, a two-dimensional acoustic image is usually generated. However, the lotus root is uniformly-shaped and centimeter-sized, therefore, high accurate three-dimensional acoustic imaging is required for specific detection. For the construction of a centimeter-scaled, three-dimensional acoustic image, a positioning system with high accuracy millimeter-scaling is necessary. However, the accuracy of the current on-ship positioning systems, such as the DGPS (Differential Global Positioning System) and the RTK (Real-Time Kinematic) systems, are more than 3 m and 0.02 m, respectively [4,5]. In addition, the accuracy is always affected by the ship's handling and natural factors, such as wind and surf. Therefore, higher resolution and more robust acoustic measurement systems, for the construction of an accurate three-dimensional acoustic image to detect the centimeter-sized lotus root, is needed.

In this study, an automatic non-destructive three-dimensional acoustic coring system that visualizes the space under the water bottom was newly developed and tested for the detection of a centimeter-sized natural lotus root in a small pond.

2. Materials and methods

A block diagram of the non-destructive three-dimensional acoustic coring system for detection under the water bottom is presented in Fig. 1. The system mainly comprised a two-dimensional (2D) waterproof stage controlling unit (Fig. 2: custom-made, Arc Device, Koganei, Japan) and acoustic measurement unit. The stage frame was 1.2 m in width, 1.2 m in depth, and 0.6 m in height. Acoustic transducers were attached to the front edge of a pole extending from the moving stage. The stage unit was electrically controlled through a notebook personal computer on which original software programed on a Labview platform (National Instruments, Austin, TX) was installed. The moving step of the stage varied from 0.001 m to 1.0 m and the moving precision was 0.0001 m in X and Y directions. The acoustic measurement unit consisted of a one-channel transmitter (diameter of 0.07 m; custom-made by Honda Electronics, Toyohashi, Japan) and eight-channel receivers (TC4013, Teledyne Reson, Denmark). An NI-DAQ device (National Instruments, Austin, TX) generated a square-wave pulse with a center frequency of 100 kHz. Here, we selected the frequency of 100 kHz for two main reasons: (i) size and (ii) depth of the lotus root. In our preliminary survey, the size of mature lotus root was about 0.03–0.05 m in diameter and ~0.3 m in length. The ratio of the target size to wavelength strongly affects the echo intensity from the target. In the case of medium silt (sound speed = 1540 m/s [8]), wavelength was about 0.03 m at 50 kHz. Therefore, a higher frequency of more than 50 kHz is suitable for the detection of lotus root considering the diameter of lotus. However, a high-frequency acoustic wave is highly attenuated in the sediment. According to the preliminary digging survey, the lotus root was distributed from

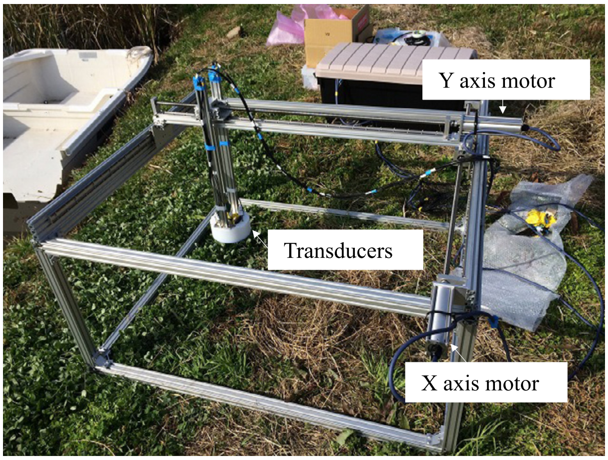

Fig. 2. Photograph of the waterproof stage frame. The stage frame is 1.2 m in width, 1.2 m in depth, and 0.6 m in height. The position of the stage is electrically controlled through a notebook personal computer.

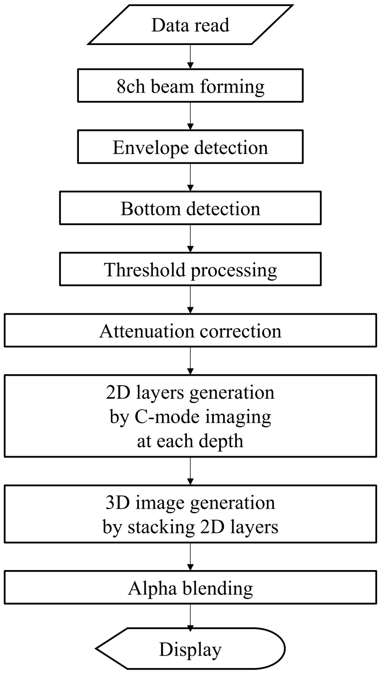

Fig. 3. Flow of 3D acoustic image processing.

0.2 m to 0.6 m. In the case of 0.5 m depth, round-trip propagation distance of acoustic wave is 1.0 m, and attenuation in the sediment can be estimated using the Biot-Stoll model [8,9] (ex. medium silt: 95 dB/m at 200 kHz, 55 dB/m at 100 kHz, and 30 dB/m at 50 kHz). Thus, the attenuation is greatly different with frequency difference, so we selected 100 kHz in the system [10]. The layout of these transducers is shown in Fig. 1. In this case, the directivity (−3 dB) of the transducers was calculated to be about 4.6°. The wave was amplified to 80 $V_{peak\text{-}peak}$ by a power amplifier (Honda Electronics, Toyohashi, Japan) and applied to the transmitter. The reflected from the surface and from under the water bottom was converted into electrical signals by the receivers. The received signals were amplified to 40 dB by a pre-amplifier (CA-251F4, NF, Yokohama, Japan) and converted to digital data with 16-bit resolution and a 1-MHz sampling rate. The system automatically repeated the operations of stage moving, stage stopping, and acoustic measurements in the 2D area (X and Y). The area was set on the program before the measurement.

To detect a buried target under the water bottom, a 3D acoustic image was constructed following the data processing flow presented in Fig. 3. First, raw data of each channel were read and eight-channel data were simply averaged without a time difference. Then the beam was focused on the sound axis (center axis of the transmitter). Next, the amplitude of the absolute value of the Hilbert transform of the corresponding analytical signal of the data was computed. After envelope

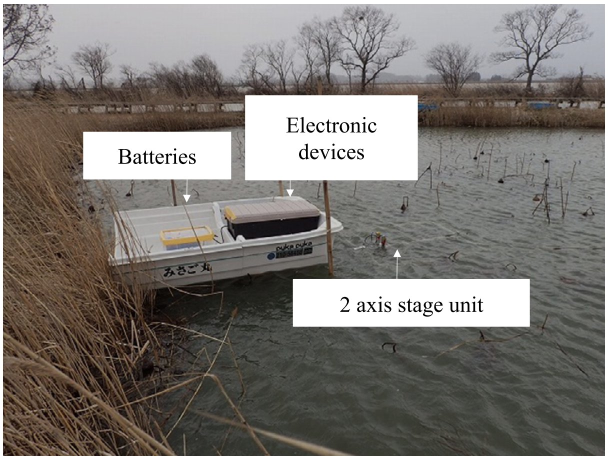

Fig. 4. Field setup. The stage control frame with transducers was set on the pond bottom and other electronic devices and batteries were put on a small boat.

detection, the receiving times were recorded at each horizontal position when the received signal reached a maximum amplitude for the first time. Here, the time is the arrival time of the wave reflected from the water bottom. The reflected signal from under the water bottom was highly attenuated owing to the wave propagation distance and this signal reduced the clarity of the acoustic image. Therefore, the amplitude was corrected by attenuation coefficient α [dB/m] and wave propagation distance. A data sample with an amplitude below a noise threshold was treated as noise and set to zero (black level in an image). To visualize the buried target, 2D cross-sectional acoustic images at each depth were generated using scanned data for the X–Y plane based on ultrasonic C-mode imaging [11]. On a graphical user interface, we could then easily access the 2D layer at any depth. In addition, a 3D acoustic image was reconstructed from these layers by stacking and alpha-blending processing [12]. Finally, a smooth 3D acoustic image of the space under the water bottom was constructed.

The field experiment was performed in a small pond adjacent to Lake Izunuma. The eutrophic water and soil conditions in the pond were similar to those in Lake Izunuma and a large portion of the pond has been dominated by lotus. In addition, the pond was suitable for the setting up of the monitoring system and allowed easy access to address any measurement problems. The pond was thus considered suitable for testing the observation system. The water depth of the pond was about ∼1.3 m and the water temperature was 4.0 °C. The stage control frame with transducers was set on the pond bottom and other electronic devices and batteries were put on a small boat (Fig. 4). The boat was anchored to keep its position against the wind. The measurement area was set to 0.8 m in the X direction and 0.85 m in the Y direction, and the stage was moved in the area with step intervals of 0.01 m; hence, 6966 received signals were recorded by each of the eight channels. There were 1600 recorded data points for a signal. As mentioned above, the target depth of lotus was estimated to ∼0.6 m. Therefore the data length of 1600 points was enough to record the signal from lotus root. The surfaces of the transducers were set to a height of 0.2 m above the bottom of the stage frame. The recording time was about 14 hours. The measurement began at 15:38:10 on 10 March 2015 and ended at 5:28:52 on 11 March 2015.

In addition to the acoustic measurement, conventional cylindrical coring using a core sampling tube was conducted. The tube had a diameter of 0.1 m and length of 1.0 m. Two cylindrical samples were cored in the acoustic measurement area (Fig. 5). The sampling positions were measured by staff before the coring. The coring operation was ended when the tube could penetrate the sediment no further. All operations were carefully conducted by a diver who was professional for underwater work. After the coring, the cylindrical sample was sliced by a metallic slicer at intervals of 0.02–0.03 m. The density of grains, gravimetric water content, and grain size were analyzed for each slice (Teijin Eco-Science Ltd., Tokyo, Japan). The parameters were analyzed in accordance with JIS (Japanese Industrial Standard): JIS A 1202 for density of grains, JIS A 1203 for gravimetric water content, and JIS A 1204 for grain size. The error bars of the values were reported to less than 3% [13].

3. Results and discussions

A 3D acoustic image was constructed and the space under the water bottom was visualized as shown in Fig. 6. The spatial resolution of the image was 1 cm^3/voxel. The origin is the start position of the measurement. Some broken lotus rods were found on the bottom surface. In this case, we adjusted the attenuation coefficient α for the image correction on GUI (Graphical User Interface) and set the value to 30 [dB/m].

The length of sample 1 was about 0.71 m and that of sample 2 was about 0.59 m. The grain density, gravimetric water content, and grain size distributions are shown in Fig. 7. Grain densities were almost constant in both samples. The gravimetric water content reduced with the slice position until it became constant around the position at 0.3 m. In addition,

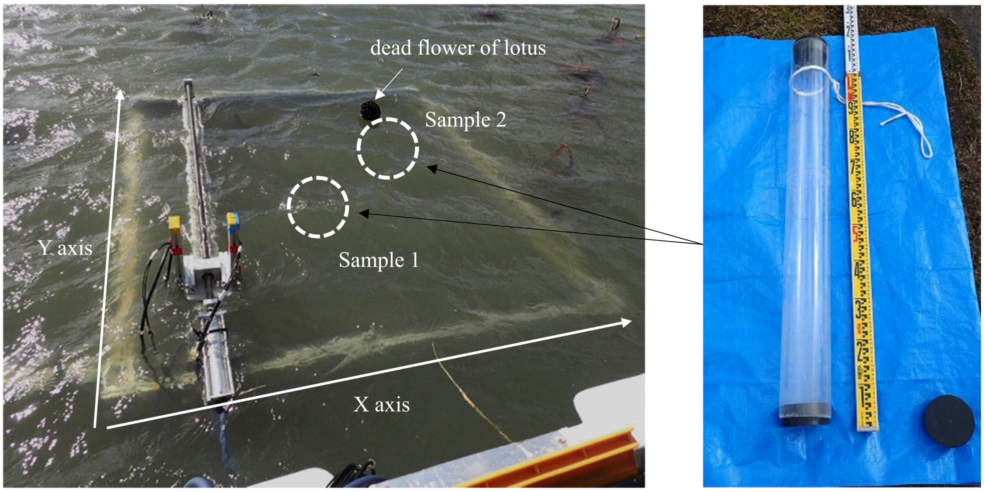

Fig. 5. Sampling positions in the acoustic measurement area. A cylindrical acrylic tube with a diameter of 10 cm and length of 1.0 m was used for the sampling.

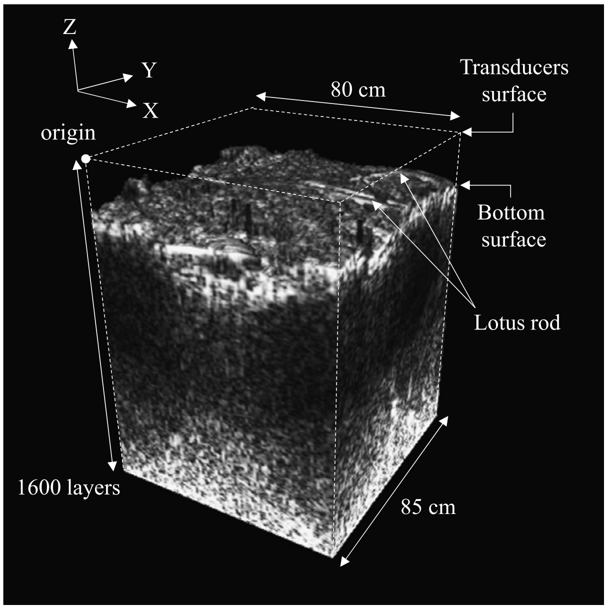

Fig. 6. 3D acoustic image. The space resolution in the image is 1 cm^3/voxel.

in sample 1, the gravimetric water content began to decrease again around 0.62 m and reached a minimum of 37.1% at the end of the sample. The distributions of median grain sizes for each slice are shown in Fig. 7 (c). In sample 1, the median grain size dramatically changed at around 0.62 m and had a highest value of 0.18 mm at the end of the sample. The results reveal that the texture of sediments changed at a depth of around 0.62 m and the density increased. According to engineering classification, the materials were divided into CsS (cohesive soil mixed with sandy soil) and SCs (sandy soil mixed with cohesive soil) at the border. Furthermore, a piece of natural lotus root was directly found at around 0.54 m in sample 2 (Fig. 8). The diameter of the root was measured with a ruler to be 0.025–0.030 m.

Cylindrical acoustic samples were constructed so that they could be compared with the directly cored samples (Fig. 8). The diameters of the acoustic samples were 0.1 m. In acoustic sample 1, there was a clear border of layers, where the amplitude of the reflected wave changed greatly, around the 891st layer as shown in Fig. 9 (a). In acoustic sample 2, a strong reflector was found around the 912th layer as shown in Fig. 9 (b). The reflector would be the lotus root because there were no other objects that could reflect the wave strongly. The C-mode images at layer 895–925 obtained from the transducers are shown in Figs. 10. The strong reflector was detected around the upper right in the image. This area is consistent with the cylindrical coring position for the core sampling tube. The reflector began to appear in the image at the 900th layer and disappeared from the image at the 925th layer. The amplitude from the reflector had a maximum value

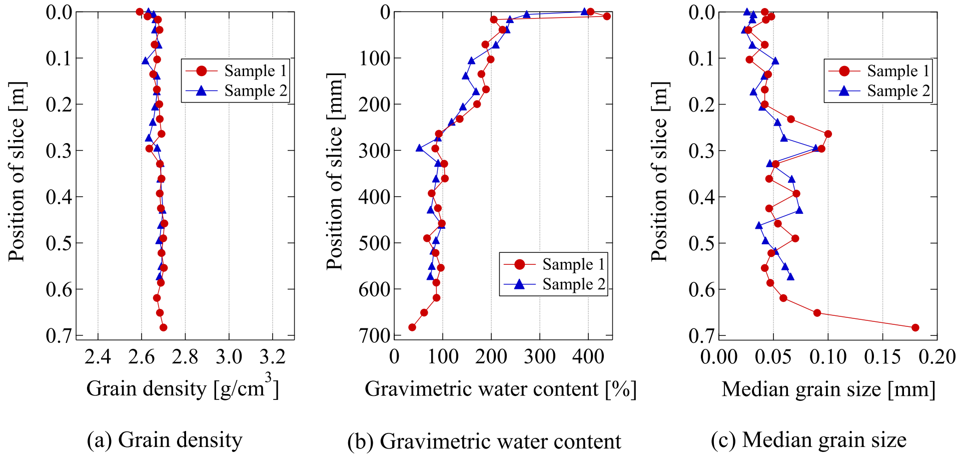

Fig. 7. Depth variation of characteristics of sediments: **a** grain density, **b** gravimetric water content, and **c** median grain size. Red circles are the results for sample 1 and blue triangles are the results for sample 2.

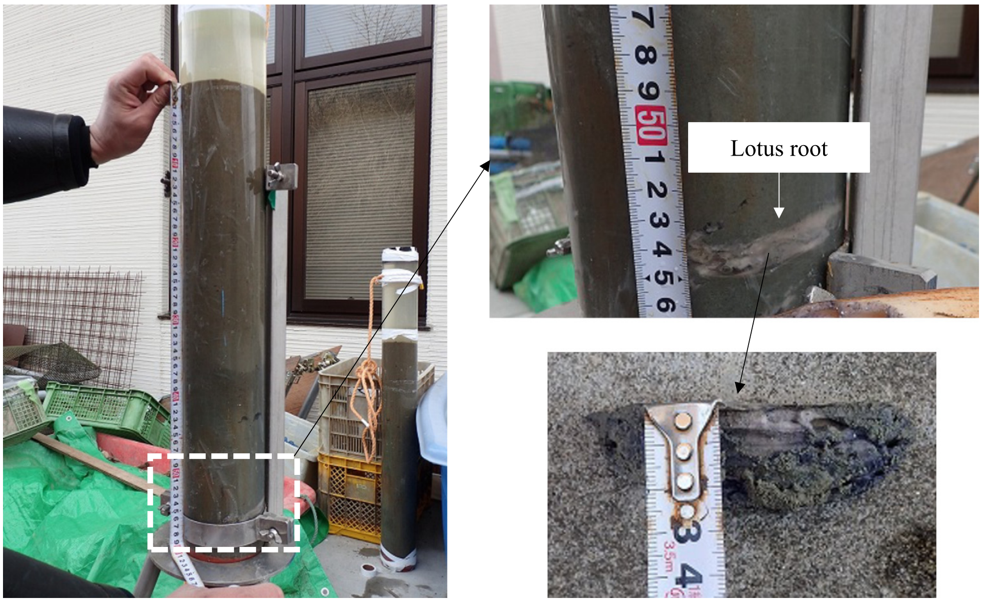

Fig. 8. Sampled lotus root is found in cylindrical core sample 2 at a depth of about 54 cm.

at 0.69 m in the X direction and 0.78 m in the Y direction. There were 686 layers between the bottom surface and the strong reflector, corresponding to a propagation time between the bottom surface and lotus root of 0.686 ms. As previously described, the distance between the bottom surface and lotus root was 0.54 m in sample 2; therefore, the average speed of the propagation wave was estimated to be about 1574 m/s. Furthermore, using the average speed, the distance between the bottom surface and the border of layers in acoustic sample 1 was estimated to be about 0.58 m. As mentioned above, the texture of sediment changed around 0.62 m in the directly cored sample, and there was thus a difference between the results of the acoustic and direct samplings of about 0.04 m. For a slice interval of 0.03 m, the difference appears reasonable. The results demonstrate that the non-destructive acoustic coring system developed in this study can detect a small buried target of lotus root under the water bottom in the *in situ* situation. However, some issues remain for the specific detection of lotus root in the *in situ* situation. A major problem is the identification of lotus root from other reflectors (e.g. stones). We believe the echo intensity from the target, and shape of the target, will be a good indicator to recognize the target as lotus root. In addition, the temporal changes of lotus root will become a good indicator because lotus root is small in the summer and becomes larger as winter arrives. However, some additional experiments and data samplings are necessary for further discussion, and some threshold values should be determined for the specific detection of lotus root.

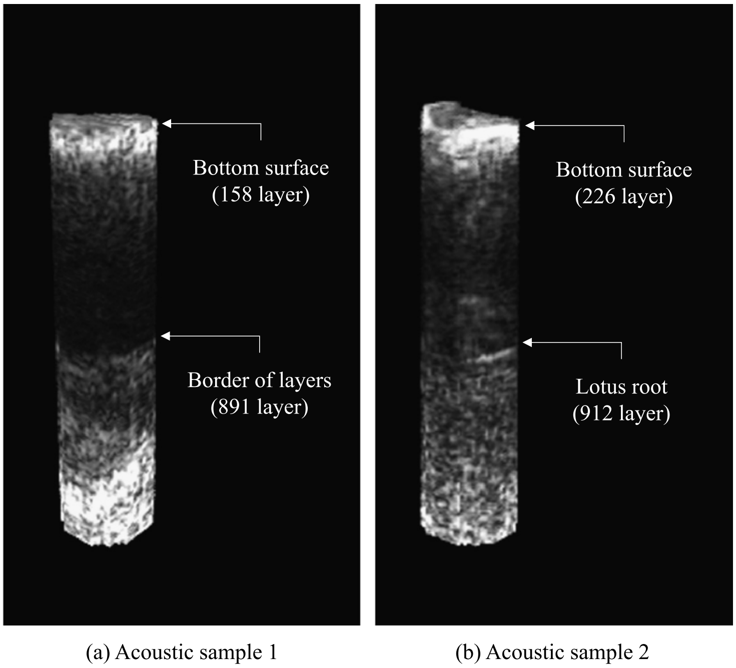

Fig. 9. Acoustic core samples corresponding to the cylindrical sampling positions 1 and 2.

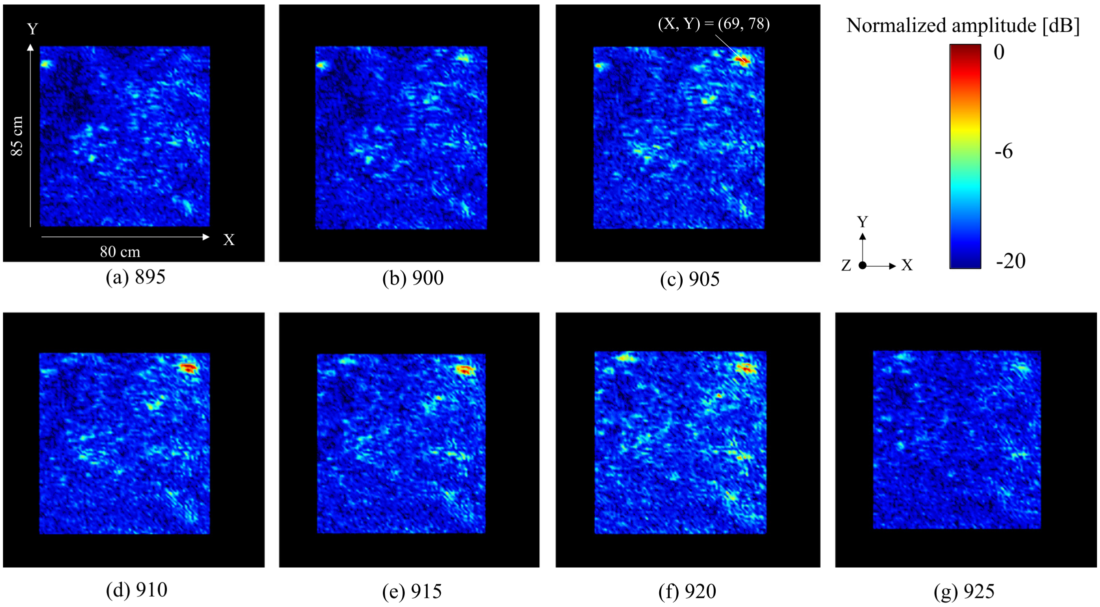

Fig. 10. C-mode image at layer 905 obtained from the transducers. The diameter of the reflector measured in the image with maximum amplitude of −6 dB is about 4.2 cm.

4. Conclusion

We developed and tested a non-destructive 3D acoustic coring system under the water bottom. A field test was conducted in a pond and the system worked without any problems arising. The measurement system can gather information under the water bottom and reconstruct the spatial status. The present study confirmed that the natural lotus root (diameter of 0.020–0.025 m) can be detected using the acoustic coring method. The measurement system is a versatile tool for the detection of lotus, the spread of which is an environmental problem in eutrophied lakes.

Acknowledgements

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.csndt.2016.01.001.

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