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The Radar Tomography Detection for the Abnormal Moisture Regions of Huge Grain Pile

[1,*] Su Yanping, [2] Lian Feiyu

[1,*] Zhengzhou Institute of Aeronautical Industry Management,
Henan, Zhengzhou, 450015, China

[2] Henan University of Technology, Zhengzhou, 450015, China

E-mail: suyanping66@163.com

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Abstract: As far as water content detection of stored-grain is concerned, cross-hole radar tomography method is used to find the abnormal water content areas in granary. Based on the basic theory of tomography, wave front ray tracing methods have been studied. Travel-time equation is used to correct refraction points before ray tracing, which improves the precision of ray tracing, and is also easy to realize. Velocity and attenuation tomography forward model were built respectively, and Least Square QR-factorization (LQSR) image rebuild methods were adopted to solve the inversion equation. Meanwhile, the properties of the two ray tracing methods were analyzed. Simulation and experimental results show that, compared to traditional methods, there is a better performance for the improved ray tracing proposed in this paper. It's proved that using cross-hole radar tomography method to detect the internal structure of huge granary is feasible. *Copyright © 2013 IFSA.*

Keywords: Ground penetrating radar, Moisture content, Tomography, Ray tracing, Image reconstruction, Least square QR-factorization.

1. Introduction

Stored-grain water content is an important work for stored-grain status monitoring. The detection of stored-grain's water content can be used to prevent stored-grain from mildewing, which has great significance for food security. At present, the main methods for grain water content detection include direct and indirect two methods. Most direct methods remove grain's water by using drying or chemical methods, which can detect grain's water content out precisely [1]. The drying method mainly includes electric oven method, decompression method, infrared heating method, microwave heating method and chemical method including distillation, Carle Fischer method and calcium carbide method and so on [2].The direct method has a very high detection accuracy but amount of time consuming, which is not suitable for on-line monitoring. Nowadays, we mainly have utilized indirect methods. The indirect methods use water-related physical quantities such as permittivity, conductivity, to finish measurement of grain's water content indirectly, which generally are faster and easier to realize online detection. These methods mainly include resistance method [3], capacitance method [4], near infrared method [5, 6] and nuclear magnetic resonance method [7], etc. All these methods have their own special characteristics but also having many limitations. For example, they can't be used to execute a depth and wide detection, need complex equipment and are usually difficult to maintain their devices. Because granaries are usually constructed to be an airtight space, traditional water content detection methods mostly are based on sampling or arrange moisture sensors or humidity sensors to collect data. The disadvantages of sampling are that the limited samples lead to an inadequate representation and the detection will take a long time; the shortcomings of assigning sensors are that the circuits are complicated and easy to aging or damage, and the measurement accuracy often has become unstable. To achieve convenient, non-destructive and accurate real-time monitoring methods, we still need to propose new solutions.

In recent years, using ground penetrating radar to detect stored-grain's water content is proposed. But the current studies usually focus on detection point by point, or a profiling of water content for whole warehouse. The general idea of the current methods is that: firstly, get dielectric constants for a pointed area by using ground-penetrating radar, then use a dielectric- water model to get a point's water content, and then use these points to form a profiling. Although using this method we can achieve a continuous water content monitoring for a large grain pile, it can not get a three-dimensional image of an abnormal water content region. Although getting more than one profile diagram, we can obtain a space simulation by arranging them, the requirement of a large number of profiles inevitably results in long measurement time consumption.

Considering the above problems, this paper puts forward a detecting method by using radar tomography to show the images of the abnormal water content areas. Through continuous scanning to grain pile, we use ray tracing method to establish a tomography forward model, by solving the model and image reconstruction, we can inverse an image of the abnormal area ever whole stored-grain area. The method has the advantages such as non-contacting, non-destructive properties and simplicity for measurement.

2. Theoretical Basis of Radar Tomography

In 1917, Austrian mathematician J. Radon put forward the famous image reconstruction equation: Radon transform, played a lead role in the formation and development of technology tomography (Computer Tomography). The concept of Computer Tomography was originally used in medical field. In the late of 1970s, Tomography technology was applied to radar to detect ground. Because the drilling mode can be obtained than surface detection more wide detection range [8], Therefore, cross-hole radar imaging theory, methods and techniques have been deeply studied[8].

3. Granary Radar Tomography Imaging

Based on the theory of cross-hole radar tomography, radar tomography measurement method is shown in Fig. 1 for horizontal warehouse. Firstly, transmitting antenna T_x and receiving antenna R_x are arranged on both sides of the warehouse. When measuring, the transmitting antenna is fixed on position t_1 and the receiving antenna is moved from position r_1 to position r_n along the warehouse wall, ant at the same time, each echo wave is recorded. Then the transmitting antenna is moved to position t_2, and the receiving antenna is moved to the position r_n still from the location r_1, thus we can obtain another group of receiving data. According to this rule, constantly moving the transmitting and receiving antenna, we can ultimately obtain $n\times n$ channel echo wave data.

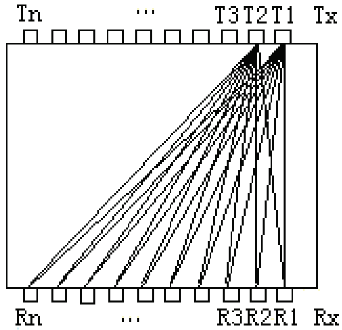


Fig. 1. Schematic diagram of measuring method.

4. Simulation and Experiment

4.1. Wave-front Ray Tracing Method

Ray tracing is a kind of effective wave field approximation calculation method, which has the advantages of fast computation and visual result. Its theoretical basis is that the main part of energy of the wave fields spread along the ray path under the conditions of high-frequency and approximation. The traditional ray tracing method includes the shooting method based on initial value and the bending method based on boundary value .The shooting method determines the receiving point's travel time through adjusting the incidence angle and density of rays form launching points and performing an interpolation to the rays mostly closed to receiving point. The bending method is first to assume and initial path between transmitting point and receiving point, and then adjust the path according to refraction law, to determine the receiving point's travel time and ray path finally. The main drawbacks of the two methods are: ① the covering density of rays is insufficient; ② it is difficult to deal with larger change of the speed; ③ it is difficult to obtain the global minimum travel time under the circumstance of multiple values; ④ the computational efficiency is low [9]. Since the 1990s, there have been some new ray tracing algorithms. These algorithms are no longer limited to the description of the ray path. However, they use equivalent wave front to describe wave field directly using Fermat or Huygens principle. The most famous methods are the shortest path method proposed by Moser [10] and wave front method proposed by Jielian Huang and others [11].

The computational method of ray tracing in wave front method is described as follow: Firstly, a region of grain pile is divided into a $N \times N \times N$ grid, select a $L \times L \times L$ ($L < N$) block in the grid, and set a lower left corner of the block as initial wave launch point, then calculate ray travel time, ray length and ray path from initial launch point to each grid point which is directly based on the principle of Huygens. Secondly, regard all grid points except the initial launch point as secondary launch points, and select another $L \times L \times L$ block to repeat the above process. Regarding each calculated ray travel time pulsing with the time from the initial launch point as the travel time of the waves from the initial launch point to the grid point, we can record the corresponding ray path and ray length until all nodes have been calculated as secondary source, then the ray tracing calculations are finished. Finally, according to the selection of the minimum travel time from receiving point, the ray path can be determined reversely.

Taking $L=8$ for example, the grid setting of wave front ray tracing method is shown in Fig. 2. When spreading along the launch point to a grid point in the same direction. waves may encounter a number of grid points, It is only necessary for us to compute ray travel-times and ray paths of the grids that their distances to launch point is minimum, which is due to that the points that the distances to the launch points are not shortest, will gradually become the points with the shortest distances to launch points when launch points move in the same directions if there are multiple grid points. As shown in Fig. 2, in the calculation of ray travel time, path and length in section 1, we only calculate the 41 grid points simply shown in Fig. 2.

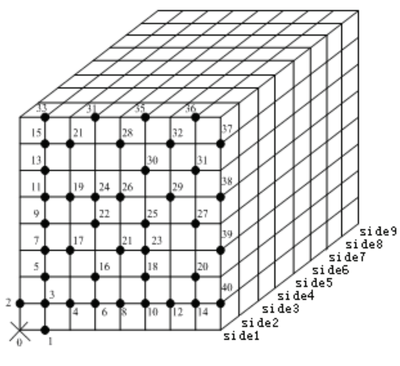


Fig. 2. Setting in wave front ray tracing method (×is launch point; ● is grid point).

4.2. Advance in Wave Front Method

As shown in Fig. 2, in the calculation box, the ray from source point to each grid point will pass grid boundary, and will be refracted on boundary if the dielectric constants of the both sides of the boundary are different (mainly due to the difference of water content between the two sides). In order to be given accurate ray path, the position of the refractive point needs to be determined precisely. In this paper, the Fermat minimum travel time principle was introduced in the wave front method. According to this principle, we can construct travel-time check equation of ray path, thus, the refraction points are determined.

Different instances of ray path correction are illustrated in Fig. 3. The dotted lines represent the interfaces between different dielectric constants. On the interfaces in Fig. 3, the total travel-time $t(x)$ can be given by:

$$\sqrt{\varepsilon_1} \cdot \sqrt{x^2 + l_1^2} + \sqrt{\varepsilon_2} \cdot \sqrt{(y-x)^2 + l_2^2} = t(x) \cdot c \tag{1}$$

According to Fermat minimum travel time principle:

$$\frac{dt(x)}{dr} = 0 \tag{2}$$

Substitute Eq.(2) into Eq.(1), we can obtain

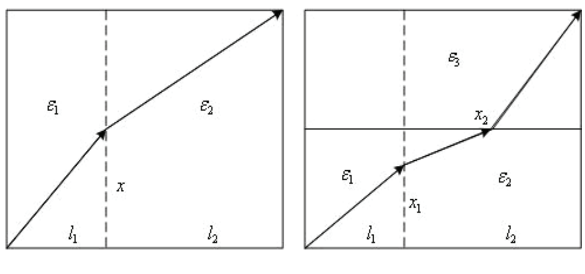
$$\left(\sqrt{\varepsilon_1} \cdot \sqrt{x^2 + l_1^2} + \sqrt{\varepsilon_2} \cdot \sqrt{(y-x)^2 + l_2^2}\right)'_x = 0 \tag{3}$$

In Eq.(3), The parameters ε_1, ε_2, l_1, l_2 and y are known quantity, so Eq. (3) is the equation about the refraction point x. Solving Eq. (3) with restricting it with $x < y$, and eliminating pseudo solutions according to the prior knowledge about dielectric constants of both side of interface, we will get the location of refraction point x.

For the condition of right angle interface in Fig. 3, we can structure the following two equations:

$$\begin{aligned} &\sqrt{\varepsilon_1} \cdot \sqrt{x_1^2 + l_1^2} + \sqrt{\varepsilon_2} \cdot \sqrt{(y_1 - x_1)^2 + x_2^2} = t(x_1) \cdot c \\ &\sqrt{\varepsilon_1} \cdot \sqrt{(y_1 - x_1)^2 + x_2^2} + \sqrt{\varepsilon_2} \cdot \sqrt{(l_2 - x_2)^2 + y_2^2} = t(x_2) \cdot c \end{aligned} \tag{4}$$

Similarly, from Eq.(2) and constraint condition $x_1 < y_1$, $x_2 < y_2$, we can determine demarcation points x_1,x_2.



(a) One interface (b)Two interfaces

Fig. 3. Different Interface in ray path correction schemes.

4.3. Extraction of First-motion Wave

The extraction of first-motion wave is an important step for radar tomography. For the radar tomography to granary, due to the limitation of granary's height and width, when antenna moves along granary's wall, the diffracted wave will have a great impact on the extraction of first-motion wave.

Assuming that the upper part of granary is air layer, the bottom is ground and the granary's wall is composed of concrete, when detecting, the granary's wall can reflect electromagnetic wave, and forms multiple reflections between granary's walls, and at the same time, produces diffracted waves on the surface of granary. The transmitted waves will accelerate when meeting air and slow when meeting high-moisture area. In addition, because the speed in granary's bottom is lower then in grain layer, the bottom of granary has no impact on extraction of first-motion wave. It is the diffracted waves that have the largest effect on extraction of first-motion wave.

We can set an appropriate time threshold to eliminate diffracted waves in air. During measuring, once the position of antenna and its moving step length are determined, the arrival time of diffraction waves at each position corresponding to transceiver antenna is determined. According to the received waveform of different position, we can set different time threshold and shield the initial diffracted waves in air, and then take the waves that emerge again as first-motion waves.

5. Wave Velocity and Attenuation Joint Tomography Imaging

Radar tomography imaging is divided into wave velocity tomography and attenuation tomography. Wave velocity tomography uses the travel time of first-motion wave to inverse image and attenuation tomography uses wave's amplitude information to inverse image. The combination of the two tomographies can reflect the electromagnetic properties better such as wave velocity and attenuation for test area completely, and its algorithm scheme is shown in Fig. 4. Firstly, we extract the travel time, amplitude and spectrum from first-motion waves; Secondly, perform a wave velocity tomography imaging using initial travel time data; At last, according to ray path obtained from wave velocity tomography and combining initial waves amplitude, perform an attenuation tomography imaging.

6. Image Reconstruction of Abnormal Water Content Area for Grain Pile

Many methods, such as Back Projection (BP), Algebraic Reconstruction Technique (ART), Joint Iterative Reconstruction Technique (SIRT), Tikhonov regularization, and Least Square QR-factorization (LQSR) [12-13] are used to solve the above tomography imaging equation. In these algorithms, the method of BP imaging is poor effective but simple and fast, commonly is used to define initial iteration model; ART method runs line by line and occupies less memory but needs more iterations; SIRT needs much memory, but has fast convergence and its result of reconstruction is better than ART method; Tikhonov regularization method has high convergence efficiency, but is sensitive to noise, under strong noise, the reconstruction process is not easy to converge; LSQR algorithm has small amount of calculation, and can take advantage of the sparsity of the matrix to simplify the calculation, so is widely used in image reconstruction. Taking LSQR method for example, this paper presented the results of the improved wave front method of ray tracing, and proved that using cross-hole radar tomography method to detecting the inside structure of barn is feasible and effective.

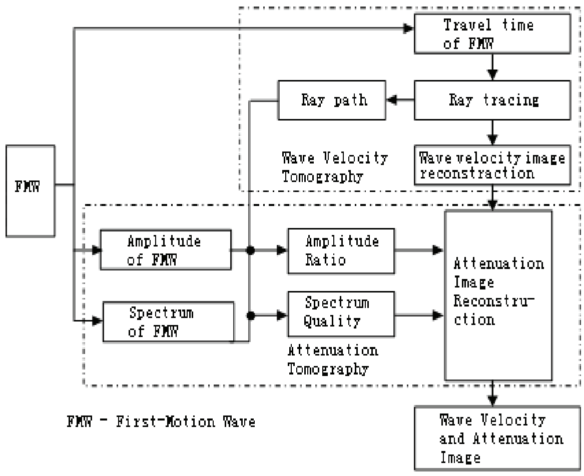


Fig. 4. The schematic diagram for Wave velocity and attenuation joint tomography imaging.

7. Experimental Results and Analyses

We used a regular model to check the effect of wave velocity and attenuation joint tomography imaging and LSQR image reconstruction. The model simulate a horizontal warehouse with 6m high and 12m width, and are full of wheat with $\varepsilon'=3.5$, $\varepsilon''=0.5$ and $Q=\varepsilon'/\varepsilon''=7$. To reduce amount of calculation, we supposed there are two abnormal water content regions with regular shape, as shown in Fig. 5. Region 1 is 2m long, 1m width, $\varepsilon'=12$ *and* $Q=6$, and region 2 is 2m long and width is same too. In experiments, we extracted a two-dimensional section that includes then supposed abnormal regions. Through computer simulating, the results of the two image reconstruction methods are shown in Fig. 6 and Fig. 7.

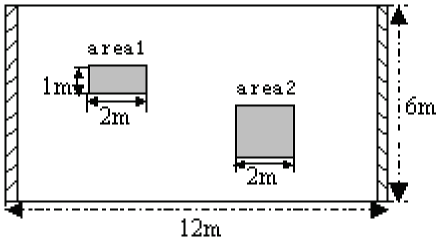


Fig. 5. Simulation Model.

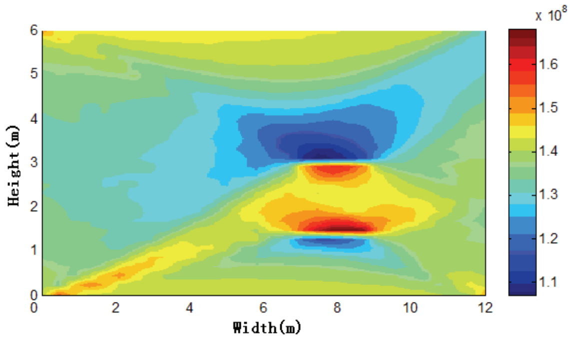
From Fig. 5 and Fig. 7, we can conclude that the effect of image reconstruction using ray path correcting is superior to that not using ray path correcting.

To show the real effects of improved wave front method, we use LSQR to reconstruct image of abnormal moisture region for an experimental granary. The experimental granary is 6m width and 6m height, and walls are made of wood boards with the same dielectric property as wheat. In experiments, we filled wheat into granary two times. The first time's moisture is 9 % and the second is 12 %, and the interface between the two layers is shown as Fig. 8. we divided the wheat region into 60×60 grids, and the step in horizontal and vertical direction are all 0.1 m. The shift step of transmitting and receiving antenna are also 0.1 m. The experiment platform is composed of a vector network analyzer and a Vivaldi antenna with bandwidth of 1-6 GHz and center frequency of f_c=*3.5 GHz*.

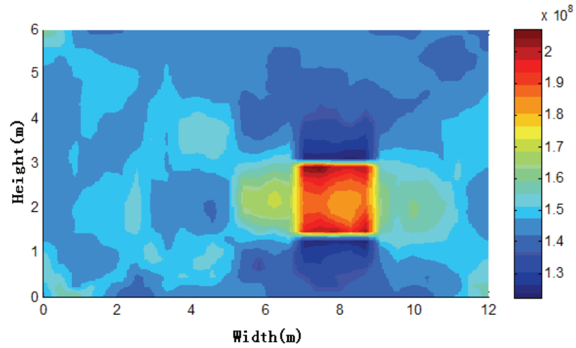
In a real warehouse, because the wall is made of concrete, the electromagnetic properties of grain pile can not be reflected well for ray tracking, so the results of the above imaging reconstruction may exists deviation compared to real circumstance, which results in misjudgement to abnormal water content region in the real warehouse. Our next work will place focus on how to confirm deviation degree and reduce the deviation.

8. Conclusion

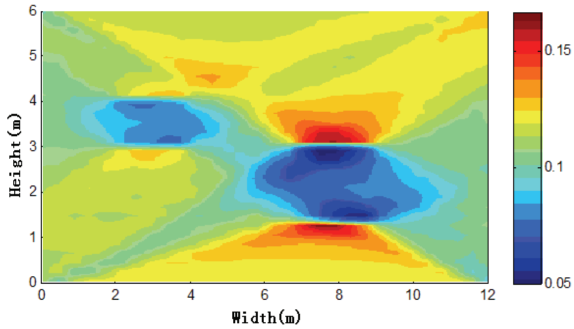
In this paper, we proposed a kind of radar tomography method to detect water content of huge grain pile, and discussed the ray tracking method using wave front method, and proposed the method that use travel time equation to correct refraction point location to improve the tracking precision. Aiming at the different boundary conditions from cross-hole detection when applying to granary detection, we construct the forward model for tomography imaging by combining Wave velocity tomography and attenuation tomography, and compared the properties of two kinds wave front methods for image reconstruction in LOSQ. The experimental results show that, using the improved wave front method for ray tracking, we can get better tomography imaging results in LSQR, Meanwhile, it also proved that using radar tomography to detect moisture content for a huge grain pile is feasible.



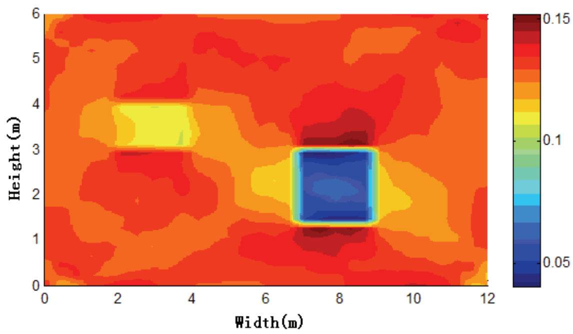
(a) Result of LSQR using unimproved wave front method (1region, 10 times iteration).



(b) Result of LSQR using improved wave front method (1 region, 10 times iteration).



(c) Result of LSQR using unimproved wave front method (2 regions, 10 times iteration).



(d) Result of LSQR using improved wave front method (2 regions, 10 times iteration).

Fig. 6. Result of wave velocity tomography imaging for simulation model.

Acknowledgments

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