Acoustic Signal Imaging Method Based on Synthetic Aperture Focusing and Full Matrix Capture

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Abstract. In order to observe and understand the effect of acoustic signal detection more intuitively, imaging analysis is needed to obtain clearer detection results, and the detection situation is analyzed manually. The commonly used imaging method is B-scan imaging, which is also widely used in medical imaging. In this paper, an acoustic signal imaging method based on synthetic aperture focusing and full matrix capture is proposed. The application of synthetic aperture focusing method in acoustic signal imaging was improved. Hilbert transformation was used to construct complex signal sequence, and the imaging processing process of full matrix method is proposed. From the aspects of data acquisition, analysis and processing, the echo signals are analyzed, and the differences between synthetic aperture focusing and full matrix method in acoustic signal imaging are compared.

Keywords: Acoustic signal imaging, Synthetic aperture focusing, Full matrix capture.

1. Introduction

At present, acoustic detection technology is relatively mature in testing principle, and some products have been applied. However, there are many shortcomings in some technical problems, such as complex structure noise, large amount of data imaging, data storage and transmission, real-time detection and other aspects, which are worth studying and analyzing. In this paper, the echo signal characteristics of acoustic detection are studied by combining theory with experiment, and the key technology of acoustic detection imaging is studied and analyzed by combining these characteristics.

As for imaging technology, echo direct imaging has long been applied to practical industry. As for the indirect data imaging method, due to the large amount of calculation and poor real-time imaging, the current research mainly applies the synthetic aperture method and the full matrix acquisition method in the array probe imaging, and carries out the imaging research through a relatively complex and large amount of calculation. Current imaging research is limited by experimental environment, geometric model of detection objects, computing power and other aspects, and the vast majority of research results, effects and real-time performance are relatively mediocre, which is also a very important research area.

In this paper, the superposition method of the post-processing method of the total matrix acquisition is studied, the improved method of synthetic aperture focusing and the imaging process of the total matrix acquisition are proposed, and the differences between the total matrix acquisition and synthetic aperture focusing are compared.

2. Synthetic Aperture Focusing Imaging

Synthetic aperture imaging methods commonly used method is a kind of acoustic detection, is the main principle of the acoustic sensor in the process of scanning experiment, after a position for echo, move a distance, repeat send incentive and receiving the echo data, for each focus imaging points, can through the different echo after a certain time delay were overlapping, this can increase the echo information of the imaging point and improve the resolution.

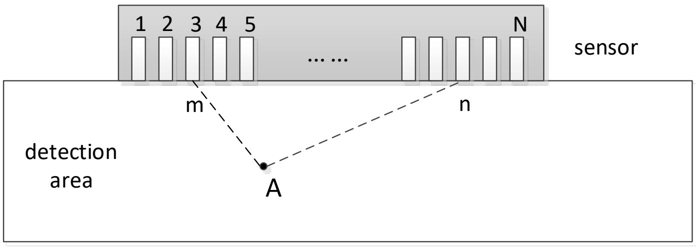


Figure 1. Synthetic aperture imaging principle based on phased array

The phased array method has been introduced into synthetic aperture imaging. As shown in Fig.1, it is not necessary to move the sensor array, but only need to switch between different sensor array transceivers to obtain echo data similar to the above method.

In the imaging process, assuming that the array has N array elements, phased array can be used to obtain N2 echo waveforms. In the imaging process, when the m probe transmits and the n probe receives each imaging point, the time delay can be obtained as:

$$
\begin{aligned}
l_m &= \sqrt{(x_A - x_m)^2 + y_A^2} \\
l_n &= \sqrt{(x_A - x_n)^2 + y_A^2} \\
t_{delay} &= t_m + t_n = \frac{l_m + l_n}{c}
\end{aligned}
\tag{1}
$$

Where x_A, x_m and x_n are the horizontal coordinates of point A, the m sensor and the n sensor respectively, t_{delay} is the time delay and c is the speed of acoustic signal. After a delay, the waveform is superimposed to form a new sequence of waveform superposition. Usually, the maximum value in the sequence is taken as the relative pixel value of the point.

$$
\begin{aligned}
W_A &= \sum_{i=1}^{N^2} Shift(W_i, t_{delay\_i}) \\
V_A &= \max(|W_A|)
\end{aligned}
\tag{2}
$$

Where W_A is A point waveform superposition, V_A is pixel value of point A, W_i is the i echo, t_{delay_i} is the i delay, $Shift$ is the left shift operation, and is completed with zero at the end.

Synthetic aperture imaging method, because multiple channels of echo signal are used in synthetic aperture, carrying large information. However, in single array measurement, each imaging processing echo is a single echo signal, and the transverse resolution of vertical acoustic beam propagation direction is very poor, and the imaging range of the detection object is expanded, making it difficult to determine the accurate position.

3. Echo envelope extraction based on Hilbert transform

Hilbert transform is a common mathematical analysis method, a signal convolved with $\frac{1}{\pi t}$ is the Hilbert transform of the signal. Assuming that the real signal is $S(t)$, then the Hilbert transform is:

$$
\begin{aligned}
h(t) &= \frac{1}{\pi t} \\
\hat{s}(t) &= h(t) * s(t) = \int_{-\infty}^{\infty} s(\tau) h(t-\tau) d\tau = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{s(\tau)}{t-\tau} d\tau
\end{aligned}
\tag{3}
$$

The Hilbert transform can be interpreted and expressed using the Fourier transform:

$$H(\omega)=F\{h\}(\omega)=-i\cdot\mathrm{sgn}(\omega)$$
$$\mathrm{sgn}(\omega)=\begin{cases}1,\omega>0\\0,\omega=0\\-1,\omega<0\end{cases} \tag{4}$$

Therefore, it can be obtained:

$$F\{\hat{s}\}(\omega)=H(\omega)\cdot F\{s\}(\omega) \tag{5}$$

The Hilbert transform shifts the positive frequency by -90 degrees and the negative frequency by +90 degrees.

In practical applications, in order to better obtain the energy level of the signal, the original signal and Hilbert transform are usually composed of complex signals: $\tilde{s}(t)=s(t)+j\hat{s}(t)$, In detection, $s(t)$ is echo, $\hat{s}(t)$ is its Hilbert transform, $\tilde{s}(t)$ is the constructed complex signal, and its amplitude and phase are:

$$|\tilde{s}(t)|=\sqrt{s^2(t)+\hat{s}^2(t)}$$
$$\arg\tilde{s}(t)=\arctan(\frac{\hat{s}(t)}{s(t)}) \tag{6}$$

In Fig. 2, the original signal $s(t)$ is a sinusoidal signal plus Gaussian window processing. Hilbert transformation is performed on it and the mode of $\tilde{s}(t)$ is constructed, which $\tilde{s}(t)$ is the envelope $|\tilde{s}(t)|$ of the original signal. Therefore, the complex signal obtained by this construction method contains good amplitude information, and the complex signal is often used in signal processing.

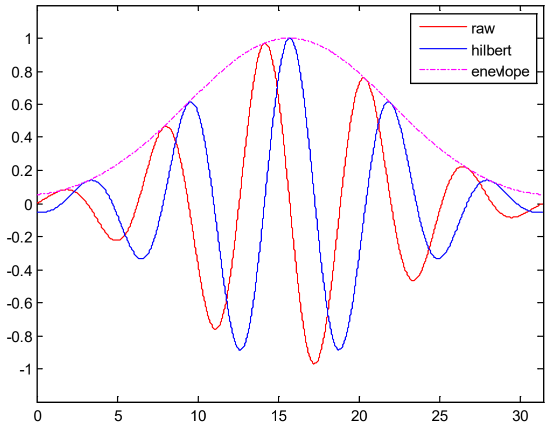


Figure 2. Hilbert transform envelope information

4. Full Matrix Capture Imaging

4.1 Basic Principle

Full Matrix Capture (FMC) is a data acquisition method for imaging applications based on multi-channel echo capture. For a linear sensor array, each probe sends and receives, and the full-time signal of the combination of all possible transmitting array elements and receiving array elements is obtained, as shown in Fig.3.

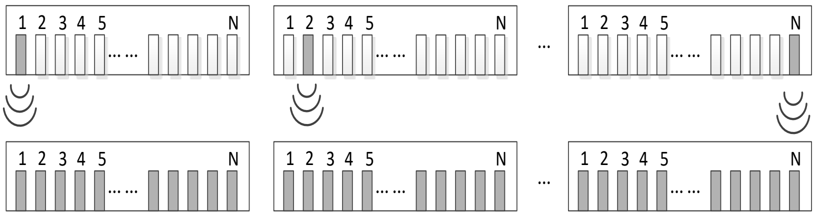


Figure 3. Full matrix capture

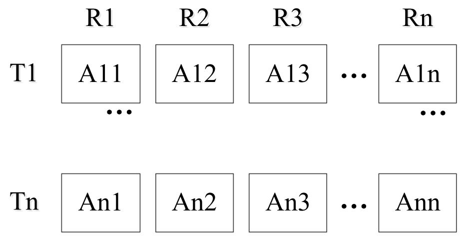


Figure 4. Data matrix model

When the transceiver switch of all channels is completed, the received signals of multiple channels have been received, and all echo signals are combined into a matrix, as shown in Fig.4.

The post-processing imaging method after data acquisition is more important and there are many post-processing methods at present. Hilbert transform is usually used to transform the real signal into complex signal, so that its envelope is easier to detect and its amplitude is easier to calculate. Assuming that the horizontal direction of array scanning is, and the vertical direction of entering test block is, the basic calculation method of pixel value at point is:

$$I(x,z) = \left| \sum h_{tx,rx}(t_i) \right| \tag{6}$$

Where, tx and rx are the probe labels of transmission and reception respectively, are time delay, and represent the complex signal sequence constructed.

4.2 Post-processing Analysis of Full Matrix Acquisition

In the post-processing imaging of the total matrix method, the Hilbert transform is used to construct the complex signal for superposition. The mode of the complex signal represents the amplitude of each point of the envelope. There are two ways of superposition imaging, one is superposition of the complex signal after superposition, and the other is superposition of the complex signal after superposition, which can be expressed as follows:

$$\begin{aligned} M &= \sum \left| h_{tx,rx}(t_i) \right| \\ N &= \left| \sum h_{tx,rx}(t_i) \right| \end{aligned} \tag{7}$$

The expression mode of M can ensure that each superimposed signal is positive, which can enhance the signal and make each imaging point superimposed on the amplitude. The form of N contains the phase information for superposition. The following is a simple selection explanation through theoretical and simulation experiments.

In theory, if the original real signal is $s(t)$, and its Hilbert transform signal is $\hat{s}(t)$, then discretization is:

$$\begin{aligned} M &= \sum \left| s(t) + j\hat{s}(t) \right| \\ N &= \left| \sum (s(t) + j\hat{s}(t)) \right| \end{aligned} \tag{8}$$

For the size relationship between M and N in Equation (8), the expansion analysis can be carried out as shown as:

$$\begin{aligned} M &= \sqrt{s^2(1)+\hat{s}^2(1)} + \sqrt{s^2(2)+\hat{s}^2(2)} + \sqrt{s^2(3)+\hat{s}^2(3)} + \cdots + \sqrt{s^2(n)+\hat{s}^2(n)} \\ N &= \sqrt{s^2(1)+s^2(2)+\cdots+s^2(n)+\hat{s}^2(1)+\hat{s}^2(2)+\cdots+\hat{s}^2(n)+2\sum_i\sum_j s(i)s(j)+2\sum_i\sum_j s(i)\hat{s}(j)} \end{aligned} \tag{9}$$

The difference between the squares of M and N in equation (9) can be obtained:

$$M^2 - N^2 = 2\sum_i\sum_j \underbrace{(\sqrt{s^2(i)+\hat{s}^2(i)}\sqrt{s^2(j)+\hat{s}^2(j)})}_{P} - 2[\sum_i\sum_j \underbrace{(s(i)s(j)+\hat{s}(i)\hat{s}(j))}_{Q}] \tag{10}$$

Further comparison of P and Q in equation (10) can be obtained as follows:

$$P^2 - Q^2 = s^2(i)\hat{s}^2(j) + s^2(j)\hat{s}^2(i) - 2s(i)s(j)\hat{s}(i)\hat{s}(j) \ge 0 \tag{11}$$

The equal sign holds if and only if $s(k)=0\,or\,s(k)=\max\,or\,s(k)=\hat{s}(k), k=i\ and\ j$ .Therefore, when the original real signal is 0 and the maximum or real signal is equal to the Hilbert transform, the result of the two superposition methods is the same; otherwise, the result of superposition after modulo first is larger.

Theoretically, since the ideal defect position should be located at the peak position, the theoretical amplitudes of the two superpositions are the same at the ideal defect position, but in other positions, the method of superposition and then taking the mode of complex signal inhibits the amplitudes and plays a role of suppressing the amplitude around the defect. Therefore, this paper adopts the method of taking the mode after the superposition of the complex signal sequence at the delay point for imaging.

5. Analysis of experimental results

5.1 Comparison of different imaging overlay methods

In the simulation, Field II open source toolkit of Technical University of Denmark is adopted to simulate and generate array probe echo data. Nine hole shape defect points are set as shown in Figure 2.4. The excitation frequency is 5MHz, the number of probes is 64, and the sampling frequency is 100MHz.

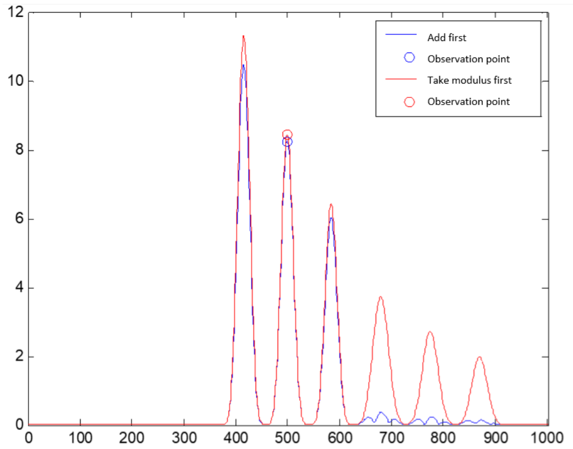


Figure 5. Stack mode simulation

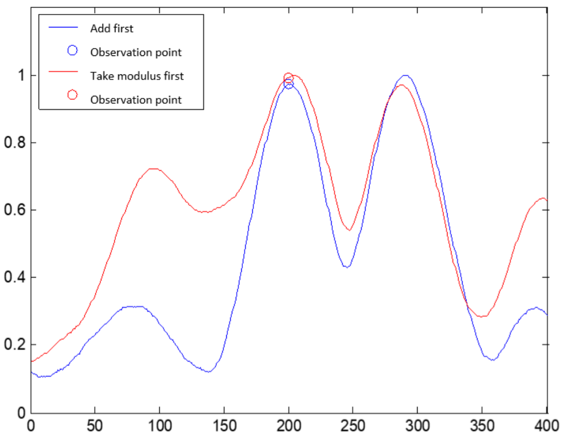
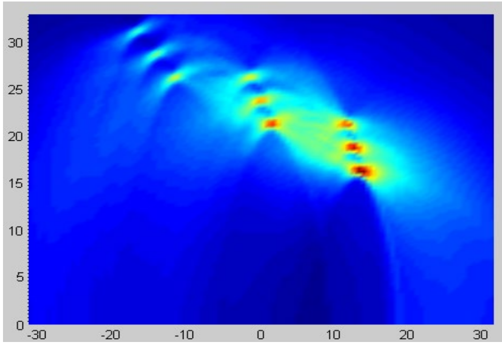


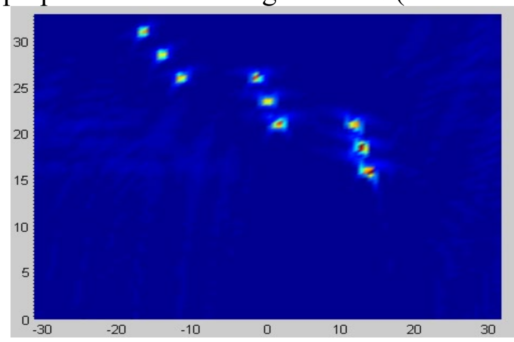
Figure 6. Experiment of superposition mode

One of the defect points is simulated by applying different stacking methods. The three probes closest to the defect point are selected to send and receive respectively, and 1000 sampling points near the observation points of 9 groups of echoes are overlapped. The results are shown in Fig.5. The increase of amplitude was inhibited by adding sum first and then taking modulus. Figure 6 shows the experimental data of 64-channel array probe, superimposed on 400 sampling points attached to the observation point. The conditions are the same as the simulation, and similar results are found around the defect observation point.

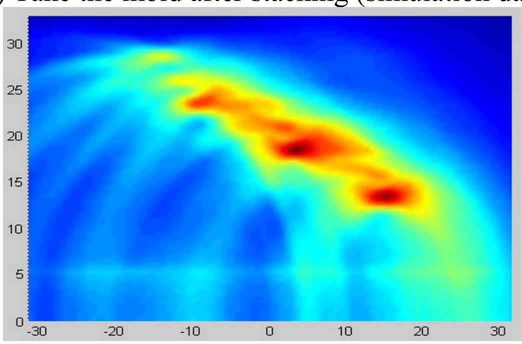
By comparing different stacking methods of simulation and experimental data, we find that the mode of adding and taking the model after the addition inhibits the amplitude of non-target points, which is exactly the expected effect of target imaging. Therefore, in future imaging, the superposition method of adding and taking modulus of complex sequence will be considered first.



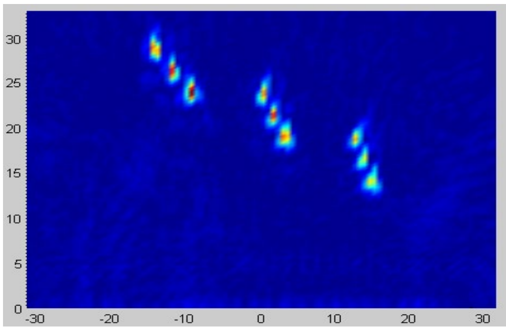
(a) Superposition after taking the mold (simulation data)



(b) Take the mold after stacking (simulation data)



(c) Superposition after taking the mold (test data)



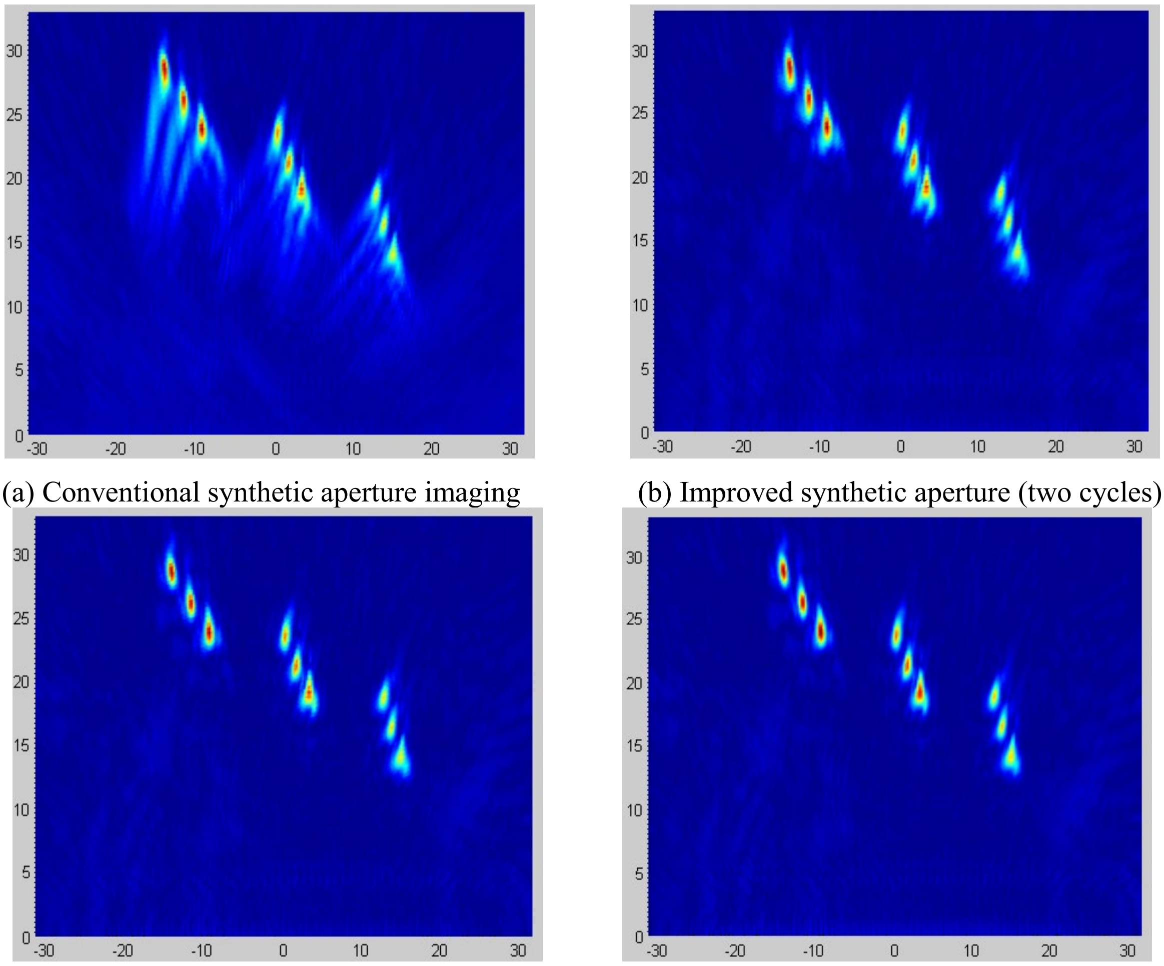
(d) Take the mold after stacking (test data)

Figure 7. Comparison of two stacking methods

In this paper, horizontal red represents the maximum amplitude of B scanning imaging, and blue represents the minimum amplitude, with corresponding amplitude values of 1 and 0. In Fig.7, (a) and (c) are the simulation and experimental results of superposition of complex signals after taking the model, and (b) and (d) are the simulation and experimental results of superposition of complex signals before taking the model. In both simulation and experiment, 5MHz excitation, 100MHz sampling, 64 channel array probe, resolution of 100*100. As can be seen from the results, both simulation and experiment, there are obvious differences in the effects of two different methods of complex signal stacking. In the simulation, the first superposition method can barely distinguish nine target points, but in the actual experimental data, the target points are seriously aliased and can only distinguish the target region. The second superposition method can distinguish the target point well both in simulation and experimental results. Through imaging experiments, it is proved once again that the superposition method of complex sequence superposition first and then modulo superposition will have better imaging effect.

5.2 Synthetic aperture method versus full matrix acquisition imaging

The imaging methods are traditional synthetic aperture method, short period improved synthetic aperture method and full matrix method, and two and half period methods are selected in short period superposition.



(a) Conventional synthetic aperture imaging (b) Improved synthetic aperture (two cycles)

(c) Improved synthetic aperture (half cycle) (d) Full matrix method imaging

Figure 8. Comparison of two stacking methods

Figure 8 for different imaging algorithm, the results of imaging of traditional synthetic aperture method to adapt to the range, but the imaging effect is not ideal, short cycle wavelength superposition results, got a huge boost but due to time delay calculation, cycle selection aspects of conditions, processing situation is special, needs analysis based on the specific situation. The full matrix method has similar effect to the synthetic aperture method, with slightly stronger amplitude in the center of the target point and slight improvement in amplitude suppression around the target point. The superposition of complex signals by the full matrix method is only the sequence of complex signals at the delay point constructed by the transformation of echo sequences of different channels.

6. Conclusion

An acoustic signal imaging method based on synthetic aperture focusing and full matrix method is proposed in this paper.

1). The synthetic aperture focusing method is adapted to acoustic signal imaging, and the calculation results are optimized by using the variable period method.

2). In the post-processing method of full matrix acquisition, the Hilbert transform is applied to construct the complex signal sequence, whose module is the original signal envelope. Different superposition methods of the complex signal sequence are analyzed theoretically and experimentally. Finally, the method of superposition first and then modulo is selected.

3). Full matrix imaging and synthetic aperture imaging contrast, through imaging contrast, the focusing ability of traditional synthetic aperture method is poor, which is greatly improved after a short period of specialization. The full matrix method has strong target central point amplitude, but it is inferior to the improved synthetic aperture method for far field suppression. Considering that the improved short-period synthetic aperture method has lower center amplitude, less computation and better focusing performance, it is a better method for B-scan imaging.

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