Non-linear Synthetic Aperture Focusing Technology Ultrasonic Imaging Applied In Nondestructive Testing

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Abstract
This paper introduces the basic principle of ultrasonic imaging system based on Synthetic Aperture Focusing Technology (SAFT). At the same time, in order to improve the axis resolution and signal to noise ratio, the correlation of ultrasonic reflected signals has been studied. Then, the author designs a non-linear SAFT algorithm based on different statistical characters of flaw signal and noise signal. Results show that in comparison with conventional time-delay SAFT algorithm, the non-linear SAFT algorithm improve the axis resolution and S/N prominently.

Keywords: Nondestructive Testing, Ultrasonic Imagines, Synthetic Aperture Focusing Technology, Correlation Coefficient

Introduction

The original ultrasonic application of SAFT followed from the radar experience in early 70'ies, and the first digital implementation of one-dimensional SAFT was demonstrated in 1976. SAFT processing is just simulating a focused transducer. In comparison with conventional imaging technique, SAFT can achieve better axis resolution using low frequency and small diameter probe [1][2].

This paper will introduce a SAFT ultrasonic imaging system applied in NDT the author designs a Lucite-specimen with six man-made flaws, use the conventional time-delay SAFT algorithm reconstructing 2D-imaging for it. Results show that conventional SAFT method cannot be used. The author studied the statistical characters of the ultrasonic signal, and draw a conclusion, the correlation coefficient of flaw signal is big, and the correlation coefficient of noise signal is puniness. Based on these statistical characters and on the principle of conventional time-delay SAFT, we modulate the signal synthetic process with non-linear means, and achieve a non-linear SAFT algorithm based on the correlation of ultrasonic signal.

1 principle of time-delay SAFT

As can be seen from Fig 1,during digital signal acquisition, a pulse-echo sensor scanned along a line with same step distance (Δx), in every sampling point, the sensor transmits an ultrasonic pulse and receives reflected waves from object. In Fig 1, we mark the signal of the reconstruct point Q with $S(i, j)$, the foundational

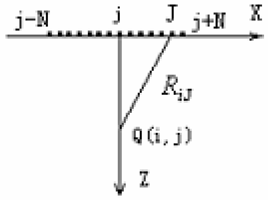


fig 1 principle of SAFT

SAFT equation is [3][4]:

$$S(i,j)=\frac{1}{2N+1}\sum_{J=j-N}^{j+N} S(\frac{2R_{iJ}}{c},J) \qquad (1)$$

Where, N the numeral of transducers, c the velocity of the sound in the media. $S(\frac{2R_{iJ}}{c},J)$ represent the reflect signal received by the j^{th} transducer which transmit distance is R_{iJ}.

2 Non-linear SAFT algorithm

We first introduce the concept of correlation before the non-linear SAFT algorithm.

Analyses of signal correlation

In signal analyses, correlation is an important conception. It describes the relation between two variables. To certain signal, we can describe two variables with a function, but to random variables, there are no such certain relations. In SAFT ultrasonic imaging, it's significance to study the correlation of signal.

We can describe the correlation between the x^{th} column signal $S(i,x)$ and the y^{th} column signal $S(i,y)$ with $\rho_{X,Y}$. here:

$$\rho_{X,Y} = \frac{\text{cov}[S(i,x),S(i,y)]}{\sqrt{D(S(i,x))D(S(i,y))}} \qquad (2)$$

$$\text{cov}(S(i, x),S(i, y)) = \lim_{M\to\infty}\frac{1}{M}\sum_{i=1}^{M}[S(i,x)-\overline{S(i,x)}]\times[S(i,y)-\overline{S(i,y)}] \qquad (3)$$

$$D(S(i, x)) = \lim_{M\to\infty}\frac{1}{M}\sum_{i=1}^{M}[S(i,x)-\overline{S(i,x)}]^2 \qquad (4)$$

$$D(S(i, y)) = \lim_{M\to\infty}\frac{1}{M}\sum_{i=1}^{M}[S(i,y)-\overline{S(i,y)}]^2 \qquad (5)$$

The value of $\rho_{X,Y}$ express the correlative degree of two column signal, It vary from –1 to +1.

To study the different correlative characters of flaw signal and noise signal, the model showed in Fig 2 are established, correlation coefficient of the x^{th} column signal to the 6^{th} column

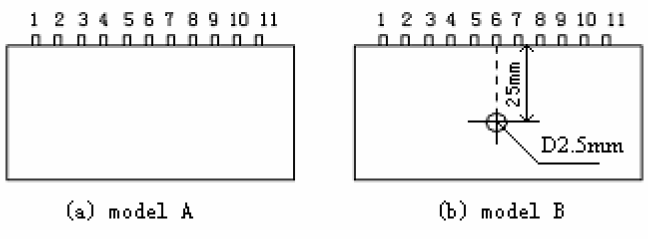
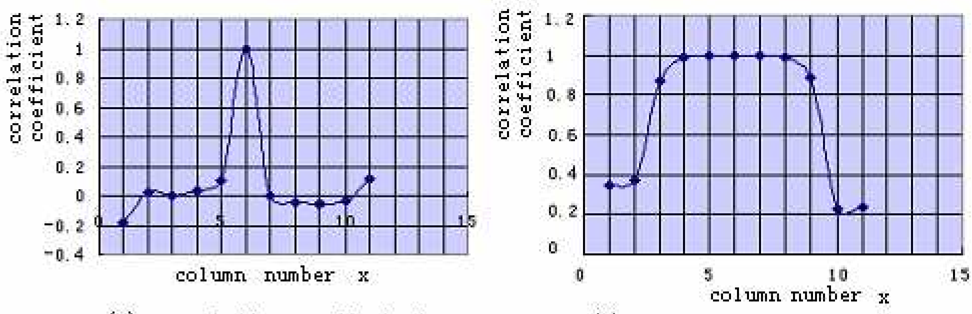


fig 2 sample model

signal are accounted by the above equation. As can be seen from the Fig 2, there are no flaws in model A, and there is a man-made flaw in model B. We sample 11 points from the two Lucite-specimens with the same step distance (Δx=2mm), and add random noise to the signal sampled from model A.



(a) correlation coefficient of model A

(b) correlation coefficient of model B

fig 3 correlation coefficient

In Fig 3, correlation coefficients of the x^{th} to the 6th column signal are given. From the above Figs, correlation coefficient of flaws is relatively big; on the contrary, it is relatively small of the noise.

2.1 Non-linear SAFT algorithm

Non-linear SAFT algorithm adopts accumulate multiplication processing before signal magnitude superposition [5][6]. At the same time, based on the different correlative characters of flaws and noise, we modulate the signal magnitude by non-linear means before signal magnitude superposition. The non-linear SAFT equation is:

$$S(i,j)=\sum_{J=-N+km}^{N-km}\{\prod_{k=-n}^{n}\psi(\rho_{J,J+km})\,S(\frac{2R_{iJ}}{c},J+\mathrm{km})\} \qquad (6)$$

Where, m is superposition step distance, n is superposition rank. Here, we adopt m=n=1. The $\psi(\rho_{J,J+km})$ in equation 6 is function related to correlation coefficient, we called it non-linear coefficient function. For non-linear coefficient function, we request it magnify the signal magnitude when the value of $\rho_{J,J+km}$ is relative big, or else attenuate the signal magnitude. Here, we can adopt $\psi(x)=x\exp(x)$ and $\psi(x)=\exp(x)$.

3 Experimentation

To test the axis resolution and S/N of different SAFT algorithms, we reconstruct ultrasonic imaging for the specimen with different SAFT algorithms such as time-delay

SAFT algorithm and non-linear SAFT algorithms based on different non-linear coefficient function.

3.1 Transducer and specimen

The frequency of the transducer adopted in the test is 5MHz and the diameter is 6.0 mm. The size of the specimen is show in fig 5, there are six Man-made holes in the Lucite -specimen which diameters are 2.5 mm.

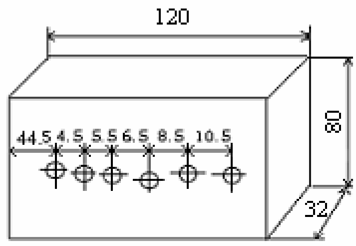
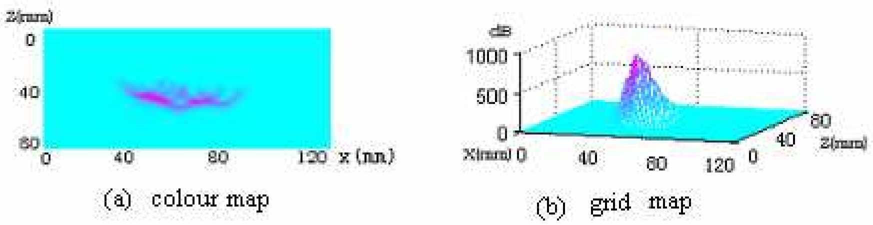


fig 5 lucite-specimen (mm)

3.2 Testing results

Reconstruct imaging for the specimen showed in Fig 5, Δx=2mm.

Fig 6 shows the ultrasonic imaging of Time-delay SAFT algorithm, we can find the axis resolution and the signal to noise ratio are very low, the six man-made flaws can't be distinguished from each other at all.

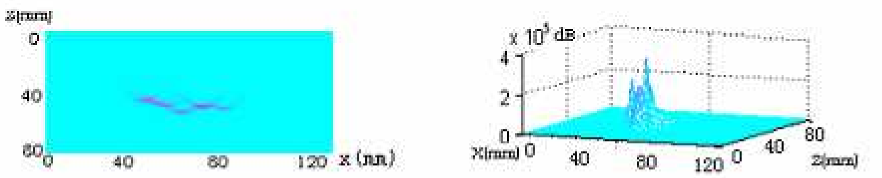


(a) colour map (b) grid map

fig 6 Imaging of time-delay SAFT

The ultrasonic imaging of Non-linear SAFT while $\psi(x) = 1$ is showed in Fig 7.

In comparison with Fig 6, the resolution and S/N of Non-linear SAFT ($\psi(x) = 1$) has been impoved, but we still can't distinguish all the six man-made holes.

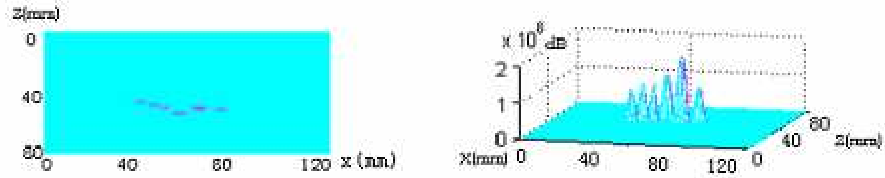


(a) colour map (b) grid map

fig 7 Imaging of Non-linear SAFT $\psi(x) = 1$

(a) colour map (b) grid map

fig 8 Imaging of Non-linear SAFT $\psi(x) = \exp(x)$



(a) colour map (b) grid map

fig 9 Imaging of Non-linear SAFT $\psi(x) = x\exp(x)$

We ameliorate the non-linear coefficient function, adopting $\psi(x) = \exp(x)$ or $\psi(x) = x\exp(x)$, then reconstruct ultrasonic imaging with the Non-linear SAFT algorithms. The ultrasonic imaging is showed in Fig 8 and Fig 9. Respectively, We can see from the above Figs, while $\psi(x) = \exp(x)$ or $\psi(x) = x\exp(x)$, the non-linear SAFT algorithms improve the axis resolution and signal to noise ratio prominently. We can distinguish all the six man-made holes distinctly.

4 Conclusions

In comparison with conventional Time-delay SAFT algorithm, the Non-linear SAFT algorithm based on correlation of signal improve the axis resolution and signal to noise ratio prominently. At the same time, different Non-linear coefficient functions have influence on the results of ultrasonic imaging. While $\psi(x) = \exp(x)$ or $\psi(x) = x\exp(x)$, the ultrasonic imaging is preferable.

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