Research on Correction and Optimization of Post-processing Imaging of Structure with Non-planar Interface Using Full Matrix Data of Ultrasonic Array

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Abstract. Ultrasonic array defect post-processing imaging and characterizing method using full matrix data has been proven to have greater ability over traditional approach. Most of the researches are focused on structure with planar interface so that array transducer can be coupled directly or with the help of common wedge. In the case of complex structure, the resolution of post-processing image using full matrix data might be dramatically decreased as the effect of non-planar interface. Some correction and optimization of original post-processing method using full matrix data are needed. In this paper, the correction and optimization method for post-processing algorithm in non-planar structure inspection are discussed. A dual-layered time flight calculation method considering non-planar interface is introduced. The difference between established method and method based on Fermat principle is analyzed and a new algorithm based on original TFM is established for complex structure imaging. Algorithm is tested with experimental array full matrix data. The performance of the algorithms is evaluated. The research result shows that for corner-shaped structure inspection, the defect image of TFM is completely coved by signal of interface reflection and noise, while the defect can be seen clearly from the image of the established algorithm. The optimization of algorithm is then discussed by changing the aperture of the imaging focusing law. The aperture used for imaging has a significant effect on imaging resolution in complex structure inspection. It is shown that the best imaging resolution might not be achieved when the whole elements of array transducer are used. The size of focusing aperture should be optimized carefully according to the geometry properties of structure. The beam path to be selected for focusing should have smaller incidence and reflection angle.

1. Introduction and Motivation

Structures with non-planar interface are widely used in aerospace industry at this time of day. They play important roles through life time. For example, parts like spars, strings, and top-hat structures consist of corners with small radius ($\leq 10$mm) as shown in Fig. 1. These structures are subject to a range of extreme operation conditions such as fatigue loading, wide temperature and humidity fluctuations, as well as chemical and environmental attack. Defects due to these effects can cause structural degradation and failure$^{[1]}$. As a result, non-destructive testing and evaluation of them become much more essential. Ultrasonic is
one of the best ways to inspect this kind of structure. However due to some factors like the access space restriction, the ultrasonic transducer is required to emit ultrasound through non-planar interface instead of from the flat part as shown in Fig. 2. The non-planar interface makes the inspection much more difficult as a result of the complex propagation pattern of the ultrasonic wave through non-planar interface.

![Image](image1.png)

**Fig. 1.** Concave structure in aerospace

**Fig. 2.** Inspecting through planar interface

Ultrasonic Array is one of the best approach to inspect structure with curve interface for its flexibility of beam steering and focusing. By controlling the delay of each element on array transducer, the ultrasonic beam can inject into structure at any designed angle and focusing depth. On the other hand, recently post-processing of full matrix data of linear array has been proven to have better accuracy in defect imaging and sizing (like Total Focusing Method - TFM) than traditional linear phased array approach [2-4]. Full matrix data is a special kind of ultrasonic data that collects the complete set of time-domain A-scan data from all the combinations of transmit and receive elements as shown in Fig. 3. TFM is a post-processing imaging algorithm that uses all the A-scan data from all elements to make virtual focusing on every detect point (not really emit focusing beam to each point in testing piece just off-line processing). It has been regarded as a golden standard of array imaging algorithm for its high defect imaging resolution.

![Image](image2.png)

**Fig. 3.** Illustration of full matrix data

TFM can also be used on structure with non-planar interface. For this type of structures curved wedges are needed to couple between array transducers and the testing piece. By modifying the time flight calculation according to Fermat Principle, B. Drinkwater [5] applied TFM to inspecting the Clifton suspension bridge chain-links. The image result showed greater signal to noise ratio than traditional array approaches such as B-scan and S-scan. By following the same algorithm TFM has been successfully used in other structures with non-planar interfaces. Unfortunately this modification is not true for general non-planar interfaces such as the sharp corner structure as shown in Fig. 4. It motivates us to do some works about TFM to increase its application fields. So in the rest part our research on the correction and optimization of TFM on structure with non-planar interface will be reported. The sharp corner structure is focused. Aluminium sharp corner structures with 5mm radius are used as experimental pieces as shown in Fig. 5.
2. Problems on Original TFM

Let $S_{tx,rx}(t)$ be the full matrix data captured from the sharp corner structure where $tx$, $rx$ stand for elements on array used for transmitter and receiver respectively. The original TFM proceeds by first discretizing the image region into a grid (in the x-z plane) as shown in Fig. 6. The signals from all the elements in the array are then summed to synthesize a focus at every point in the grid. The intensity of the image, $I(x, z)$ at any point in the scan is given by:

$$I(x, z) = \sum |S_{tx,rx}(T_{tx,rx}(x, z))|$$

where $T_{tx,rx}(x, z)$ is the time flight of ultrasonic reflected signal from $tx$ to $rx$ assuming an defect at location $(x, z)$. As B. Drinkwater recommended $T_{tx,rx}(x, z)$ is calculated by Fermat’s Principle in case of non-planar interface structure inspection. 

A system for full matrix capture (FMC) and TFM is built as shown in Fig. 7. The original TFM is used to image defect in test piece 1 and 2. As Fig. 8 shown, no defect information can be seen clearly from the TFM image. The whole picture is blurred by strong noise signal. The
result show that the original TFM can’t work correctly on sharp corner structure. Some factors of the algorithm should be corrected.

3. Time flight Correction

3.1 New Time Flight Calculation Method

The calculation of $T_{tx,rx}(x, z)$ is the core part of the TFM. The Fermat’s Principle tells us that the ultrasonic beam will take the path of least time (stationary point) through the non-planar interface. Unfortunately some researches show [6] that if the curve interface is concave like sharp corner, there may exist more than one stationary point as shown below. Worse still the beam path that satisfies the Snell’s Law may not be the least.

In order to find the beam path that satisfy both Fermat’s Principle and Snell’s Law for every element and image point pair through concave interface, a new time flight calculation method based on Snell’s Law is established. In this method, the non-planar interface is represented by NURBS expression as shown in Fig. 9. In this way the parameter interval of any curve is 0 to 1. The expression of NURBS is:

$$
p(u) = [x(u), z(u)] = \frac{\sum_{i=0}^{n} \omega_i d_i N_{i,k}(u)}{\sum_{i=0}^{n} \omega_i N_{i,k}(u)}$$

$$\alpha_n(u) = \frac{\pi}{2} + \tan^{-1}\left(\frac{dz}{dx}(u)\right)$$

(2)
According to the Snell’s Law, an equation about relationship among element on array, non-planar interface and image point in test can be easily written as:

\[
\begin{align*}
\theta_i(u) &= \cos\left(\frac{P_{ix} - x(u)}{\sqrt{(P_{ix} - x(u))^2 + (P_{iz} - z(u))^2}}\right) - \alpha_N(u) \\
\theta_T(u) &= \pi - \cos\left(\frac{Q_{ix} - x(u)}{\sqrt{(Q_{ix} - x(u))^2 + (Q_{iz} - z(u))^2}}\right) - \alpha_N(u) \\
F(u) &= |\sin(\theta_i(u)) \cdot c_{part} - \sin(\theta_T(u)) \cdot c_{wedge}| = 0
\end{align*}
\]

Obviously for every \( u^* \) that makes the equation established, the curve point \( p(u) \) is also the stationary point that satisfied Fermat Principle. The time flight \( T_{tx,rx}(x, z) \) then can be written as:

\[
T_{tx,rx}(x, z) = \frac{\sqrt{(x_x - p(u^*))^2 + z_{tx}}}{c_{wedge}} + \frac{\sqrt{(x - p(u^*))^2 + z}}{c_{part}}
\]

3.2 Beam Focusing Comparison of Different Time flight

Here a beam focusing comparison experiment between Fermat Principle and new established method is conducted as shown in Fig. 10. The array transducer has 32 elements, the pitch is 0.6mm. The testing piece has a radius \( R=5\text{mm} \) concave interface, the material is aluminum. A wedge is used to couple the transducer and the testing piece. The speed of wedge is 2337mm/s. The distance between the center of the array to the center of the concave interface \( H=7.2\text{mm} \). In this experiment the distance between focusing point and the center point of concave interface (Point O) is 20mm, the steering angle respect to the z axis is 0°, 15° and 30°.
The focusing result shows that the focusing mode has some differences between algorithm based on Fermat’s Principle and Snell’s Law. In Fermat’s case there is no beam path travels through the curved interface. However in Snell’s Case, there exists several beams travel through the beam path. It seems that those beams travel through the curve may have some effects on the TFM image.

3.3 Experiment verification

To verify the assumption, the TFM image of the sharp corner aluminum structure based on the correction of established new time flight path calculation algorithm is conduct. As Fig. 12 shown, it’s inspiring that the image has some spot that seems to be the defect on the testing path. However there still exists some unexplainable signal in the image. It means much more correction of TFM is still needed.

4. Aperture Optimization

4.1 Optimization Method

From the theoretical analysis and experiment result above, it seems that those beams that travel through the curve interface play very important roles on sharp corner structure defect imaging. The beams travel much far away from the curve zone may have a bad influence on defect imaging. Something must be done to optimize the aperture used to TFM for every
image point. The optimization aims to eliminate those elements that travel through a path that much far away from the curve zone. It’s obvious that the ultrasonic beams travel through the curve zone have much smaller incident angle and transmitted angle than beams travel through far away from the curve zone. So an aperture optimization method based on double threshold is established. In this method there exist two thresholds. One is the incident angle threshold another is transmitted threshold. Those beams path that have an incident angle bigger than incident threshold or have a transmitted angle bigger than transmitted threshold will be eliminate.

On the other hand, it is no doubt that the ultrasonic beam that travels normal to the surface will transmitted the highest percent of energy into the structure. In this way another optimization criterion is established. In this criterion only the elements in the sub-aperture are used in TFM. The sub-aperture is changed as the focus point is changed. The line connected the center of the subset and focused point is normal to the curve of interface as shown below as shown in Fig. 13.

4.2 Beam Focusing Comparison of Different Optimization

After the established aperture optimization procedure, as Fig. 14 shown ultrasonic beam that travel far away from the concave zone is eliminated as we expected.

4.3 Experiment verification

The TFM after aperture optimization is shown below. Defect can be seen clearly as shown in Fig. 15. After beam path correction and aperture optimization. The image quality of structure with concave interface (i.e. sharp corner) has increasingly improved. It proves our correction theory to be true. However there still exist several problems unsolved:

(1) For test piece2 the defect1 and defect2 can’t be defected by using the corrected TFM. Something must be improved in the future.

(2) There still exists some unexplainable signal in the TFM image. However this signal has nothing to do with the sharp corner zone.
5. Conclusion

(1) Correction and optimization of inspecting structure with non-planar interface by total focusing method is presented in this paper. First, the algorithm for calculation of time-flight in non-planar interface is built by Snell’s Law. Second, aperture optimization is recommended to avoid unwanted reflection signal from interface. The experiment result shows that the original TFM can’t be used for concave structure inspection directly. However TFM after correction can image defect in concave structure directly and has a good accuracy.

(2) There still exist some explainable signals on the defect image. Further work should be done to optimize the algorithm.

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References