ULTRASONIC INSPECTION OF TITANIUM ALLOYS WITH A TIME REVERSAL MIRROR

Najet Chakroun *
Véronique Miette *
Mathias Fink *
François Wu *
Gérard Mangenet **
Lionel Beffy **

*Laboratoire Ondes et Acoustique
Espci, University Paris VII
10, Rue Vauquelin, 75005 Paris, France

** SNECMA, Service CTPM
BP 81
Route Nationale 7
91003 Evry, France

INTRODUCTION

Ultrasonic Time Reversal Mirror (TRM) is an original solution to detect small cracks in a solid of any geometrical shape. Indeed, nondestructive testing need high resolution capabilities, high reliability and shortest control time. But the more recent techniques need an a priori knowledge of the liquid-solid interface and present limitations.The first of these uses several large prefocussed arrays, one array for each testing depth. Therefore this control system is sensitive to the arrays alignment, limited by the array precision focusing, and requires a complex mechanical follower system. A greater flexibility can be obtained by a second technique that is based on delay lines. But an accurate knowledge of the interface and a high calculs resolution are indispensable.

In the time reversal process, we take advantage of the properties of piezoelectric transducers, i.e. their transmit and receive capabilities, their linearity, and the capability of instantaneous measurement of the temporal pressure waveforms. The pressure field $p(r_i, t)$ reflected by a defect is detected with a set of transducer elements located at positions r_i and is digitized and stored during a time interval T. The detected pressure fields are then resynthetized and transmitted by the same transducers in a reversed temporal chronology (last in, first out). This is equivalent to the transmission of $p(r_i,T-t)$ and the divergent wave coming from a defect becomes a convergent wave focusing on it.

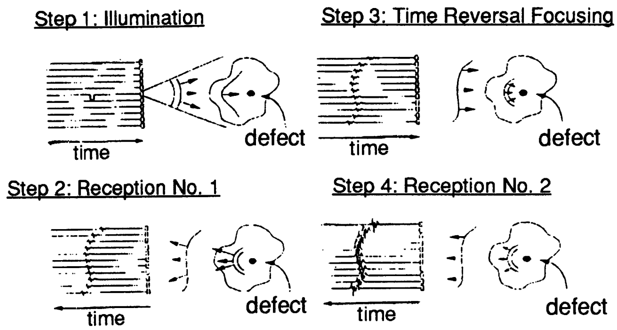


Figure 1. Time reversal process in four steps.

The time-reversal experiment requires four steps (Figure 1): in the first step, a large illuminating beam was transmitted by one or more transducers of the array. In the second, the echoes from the sample were recorded, synthetised, and time-reversed. In the third one, the time-reversed signals were re-emitted and the wave was focused on the sample defect. In the four step, the new echoes coming from the block were recorded. The amplitude of the defect is amplified: the time-reversed wave was focusing on it. This method is self-adaptative and matched to the geometry of the sample liquid-solid interface [7].
Another very attractive feature of time reversal processing is its speckle noise reduction capability. If the speckle noise results from a microstructure whose scale is less than the wavelength, the time reversal process cannot refocus on the speckle noise sources due to the loss of information during the propagation. Using this property, we developed a new signal processing technique that allows to distinguish, during the inspection, a flaw from high-level incoherent speckle noise.

In this paper, we present the time reversal process applied on a noisy titanium sample and on a titanium billet of 250 mm diameter.

TITANIUM INSPECTIONS THROUGH PLANE INTERFACES.

Basic experiments

The French aircraft company, S.N.E.C.M.A., made an important effort to improve ultrasonic inspection of titanium alloys. This study has been developed for four years in our laboratory [1,2,3,4, 5, 6]. During the elaboration process of titanium, metallurgical inclusion defects such as "hard-alpha" can appear. A hard-alpha inclusion is a localized region of alpha phase grains which have a substantially higher hardness and brittleness than the surrounding material. If not detected, hard-alpha inclusions can become crack initiation sites, and lead to component failure. The detection sensitivity of this kind of defect is limited because titanium is a noisy medium : the strong ultrasonic speckle noise is induced by the polycrystalline microstructure. A second limitation comes from the characteristics of the hard-alpha which has a low reflectivity due to a small acoustic impedance mismatch and has an irregular and unknown shape.

In the following, the experiment is carried out with a 2-D array working at 5 MHz. It is spherically prefocused with a radius of curvature made of 330 mm and it contains 121 elements. The central element is a disk of diameter 5mm and the others are annular sector elements. The transducers are distributed according to a six annuli structure of respectively 1, 8, 16, 24, 32 and 40 elements. Each element of the array is electrically matched to a 50 Ω load with a LC matching network. The total aperture is equal to 60 mm. The entire titanium block and the Time Reversal Mirror are immersed in a tank of water.

Time Reversal of signals coming from a zone containing a hard-alpha

An artificial hard-alpha defect has been located 20 mm below the plane surface. A pulse echo calibration with a classical transducer shows that it corresponds to a backscattered amplitude field equivalent to a 0.4 mm diameter Flat Bottom Hole. In this experiment, the hard-alpha is located 5 mm off the symmetry axis from the array. Let us now present in detail the fourth step needed to focus ideally on the hard-alpha.

The first incident wave is transmitted by the central element of the 2-D array. Figure 2-a shows the recorded data in grey level for the reception 1 for each of the 121 transducer elements. Data are presented in B-Scan mode, where the horizontal axis represents time (depth) and the vertical axis the transducer number. The data correspond to the logarithmic envelope of the individual echographic signals received on the 121 elements of the array. From these data, we can see the echoes coming from the front and back faces of the titanium block. Between these high amplitude echoes, we note the titanium speckle noise induced by the microstructure. This reflected sound results in a defect signal which is superimposed upon the grain noise background. Here, the defect signal can not be readily differentiated from the noise background. The fraction of the incident sound reflected depends on the magnitude and abruptness of the impedance contrast, and on the size and shape of the defect. In the second step, a 2μs (6 mm of titanium) time window is chosen after the front face echo, selecting a titanium section which origin is located at a depth of 20 mm. In the third step, the windowed data are time reversed and retransmited. After propagation the time reversed wave focuses on the hard-alpha. In the last step, we recorded the echoes coming from the block. Figure 2-c (reception 2) presents these new data. Echoes from the two interfaces still exist, but between these echoes an oscillating line clearly appears. This line corresponds to the echoes from the hard-alpha received by the T.R.M. elements. The defect signal can be readily differentiated from the noise background and the defect is detected. After a time reversal process, the signal to noise ratio increases. The T.R.M. performs in real time a Fermat surface matched to the relative positions between the T.R.M. and the defect. The hard-alpha defect is automatically detected in a section of more than 1 cm^2 around the 2-D Time Reversal Mirror axis.

A more compact presentation of the time reversal process can be implemented by adding all the 121 logarithmic envelopes of the received signals (Figure 2-b). This sum generates a single array output. In the following, this process is called « incoherent summation », because the individual data are not in phase. The logarithmic scale dynamic is 90 dB. Looking at this summation (Figure 2-d), we note that the amplitude of the defect is now 20 dB over the noise level. This summation can be implemented fastly, but it is not an optimal processing because the received signals are not usually in phase.

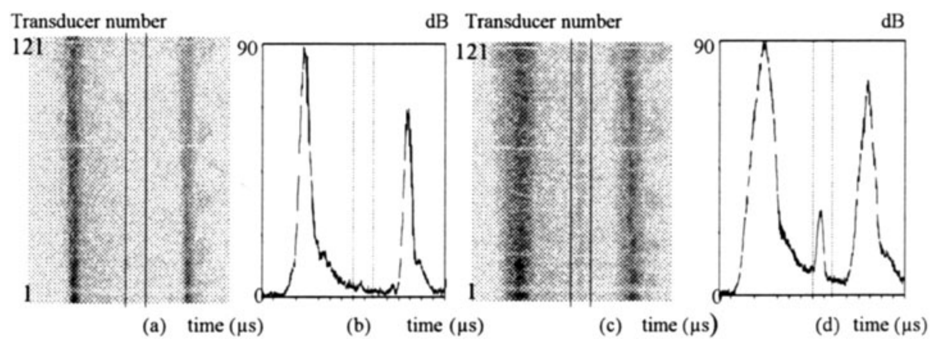


Figure 2. Incoherent summation results on a defect zone: reception 1(a,b), reception 2 (c,d)

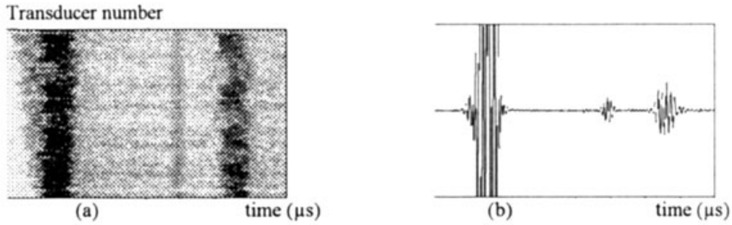


Figure 3. Coherent summation results on a defect zone

Figure 3. Coherent summation results on a defect zone

The total output signal can be improved significantly by correcting the individual signals for the differences in arrival times. A summation of all the shifted individual signals is performed to obtain a single combined signal for the array. Such a time compensating process corresponds to a coherent summation and allows to increase the echo level. The coherent summation is much more efficient than the incoherent one. Figure 3 presents the coherent summation in a linear scale, the signal to noise ratio reaches 30 dB.

The location of the 121 maximum allows to determine a curve which represents an ideal wavefront coming from the defect. Such a wavefront is a very good approximation of the Fermat surface needed to refocus on the defect from the transducer array.The obtained Fermat Surface shows a continuous aspect.

Time Reversal of signals coming from a speckle noise zone

In the second part of the experiment, the time reversal process is now evaluated with a time reversal window located in a pure speckle noise zone. Figure 4-c shows that the signal behavior does not change after one time reversal process. We do not notice any wavefront appearing in the data. In titanium, the speckle noise comes from the microstructure, whose dimension (a few μm) is small with respect to the wavelength (1.2 mm for longitudinal waves). The time reversal process cannot refocus the energy on the acoustic source of the speckle noise. This is due to the loss of information on the small details of the titanium microstructure during propagation of the backscattered wave with a 5 MHz central frequency. No peak arises from the incoherent summation of the 121 received signals : they are completely uncorrelated (Figure 4-b). If we calculate the position of the 121 maximum, we note that this position differs completely from one element to another. The obtained Fermat Surface shows a discontinuous aspect. Now, if we add all this data with the coherent summation technique, we obtain a peak amplitude which can be considered as an artifact (Figure 5) that results from an alignment of the maximum of all the individual speckle noise signals. Such a process clearly amplifies the speckle noise through a coherent summation.

In conclusion, the coherent summation is optimal when there is a defect in the zone of interest, and incoherent summation is optimal in speckle noise zone.

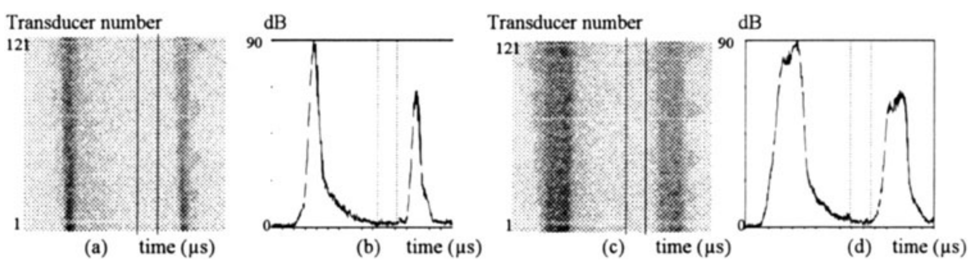


Figure 4. Incoherent summation on a noisy zone: reception 1 (a,b), reception 2 (c,d)

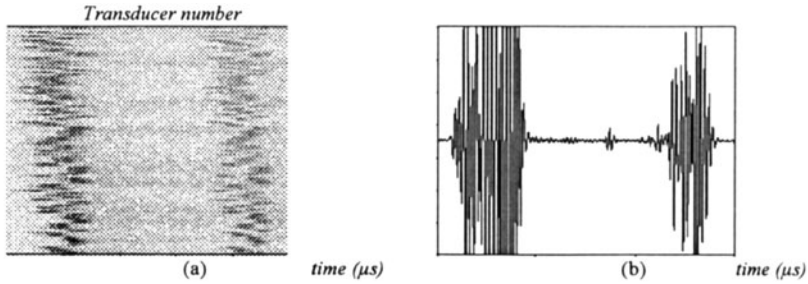


Figure 5. Coherent summation on a noisy zone.

After one time reversal, a simple trade-off consists in using only incoherent summation for all the inspections. As previously observed, the origin of the backscattered signals can be found by analyzing the Fermat surface shape. Indeed, the calculated Fermat surface is continuous in the coherent source case, and discontinuous in the incoherent one.

THE ITERATIVE TECHNIQUE

In the case of a defect signal of low amplitude, the iterative time reversal mode can be used to distinguish between speckle and defects.For the experiment we perform two iterative loops: a new time reversal operation is processed with the signals recorded and time-reversed at reception 2, and new data from the medium are recorded during reception 3.We present the results of the iterative time reversal operation in the case of a small defect and in a zone containing only speckle noise.

Figure 6-a represents, the temporal signals received on a transducer at the receptions 2 (solid line) and 3 (dotted line). They are very similar, up to an amplitude factor due to the amplification efficiency of the time reversal process. This result is linked to the fact that the echographic signals come from a coherent source of small dimension (the hard-alpha).We can note that the two waveforms are symetric.

Figure 6-b shows two waveforms come from pure speckle noise received at receptions 2 (solid line) and 3 (dotted line) on the same transducer. We note that the two signals present quick variations and seem to be random signals. The two waveforms are uncorrelated and there is no amplification in this process. The time reversal has lost the information needed to refocus on the small details of the microstructure, so there is no focusing effect.

Using these features of the time reversal technique, we developed a new signal processing technique to reduce the speckle noise : the time reversal deviation histogram.

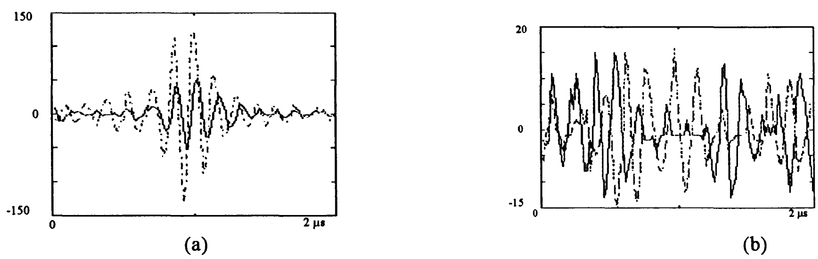


Figure 6. a. Signals from a defect received at receptions 2 (solid line) and 3 (dotted line)
b. Signals from a noisy mediumreceived at receptions 2 (solid) and 3 (dotted)

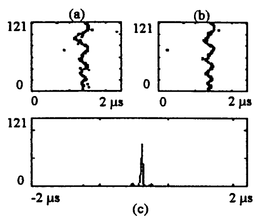


Figure 7. Defect histogram

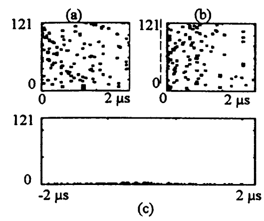


Figure 8. Noisy medium histogram

The Time Reversal deviation histogram technique:

This technique is based on the evaluation of the degree of similarity of the received wavefront after one or two operations of time reversal. A simple approach to evaluate this degree of similarity is to calculate a normalized correlation coefficient between the whole signals inside the time-reversed windows for the receptions 2 and 3.This technique is time consuming since it needs first to store the 121 signals of the receptions 2 and 3, and then to proceed to the cross-correlation. So, we have developed a much simpler approach using the concept of Fermat surface. The new algorithm compare the Fermat surface obtained after one time reversal preocedure with the one obtained after two time reversal. The Fermat surface obtained for the reception 2 and 3 are the curves which represent the 121 values of the position of the pression maximums for the iterations 2 and 3 respectively. With this technique we don't store the 2*121 individual signals but just the 2*121 maximum positions.

We present the two Fermat surface curves obtained for reception 2 and reception 3 in a case of an iterative process in a zone containing a defect in (Figures 7-a, 7-b) and in a zone containing speckle noise (Figures 8-a, 8-b). Figures 7-a and 7-b show similar continuous curves. On the contrary, Figures 8-a and 8-b show completely differents clouds of points which are randomly distributed.

The deviation of the position of the maximum is done by subtracting the reception 2 position from the 3. This operation is repeated for all the 121 elements of the array. A mean to represent the 121 values is to use an histogram presentation. The corresponding deviation histogram gives the dispersions of those 121 values of the maximum position. The y axis of the histogram represents the number of transducer and the x axis represents the time shift between the iterations 2 and 3 positions.

The two techniques, normalized correlation coefficient and the deviation histogram can be compared. A normalized correlation coefficient close to 1 corresponds to a deviation histogram with a high amplitude narrow peak whose value is nearly the number of transducers (Figure 7-c). A normalized correlation coefficient close to 0 corresponds to a spread deviation histogram whose peak value is very low (Figure 8-c). By defining a detection threshold we can distinguish speckle noise zone from defect zone.

TITANIUM BILLET OF 250 mm DIAMETER INSPECTION

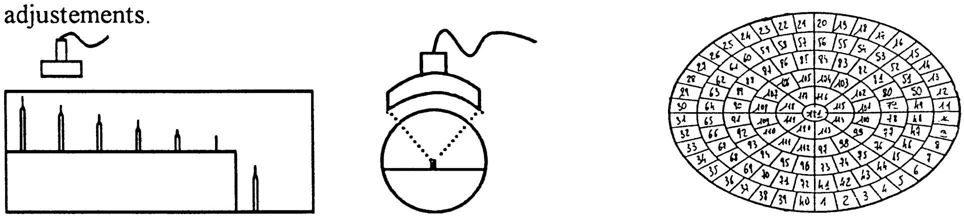
We have demonstrated the TRM ability to focus on a defect in a noisy medium or through a complex interface [7]. The next step is to inspect an entire titanium billet. This experiment presents two difficulties: the detection of deep small defects in a very noisy medium and through a cylindrical liquid-solid interface. To solve these problems, the first classical technique uses large transducers arrays. But larger transducer means shorter focal zone, longer time control and alignement problems. The other one with electronic delay lines is limited by the precision, the billet roundness and straighteness and the beam aberrations. In fact, the billet inspection is a critical test for all the NDT. These tests were performed on the S.N.E.C.M.A industrial area. The sample is a billet of 250 mm diameter with seven 0.8 mm flat bottom holes located at 5, 23, 46, 69, 91, 114 and 140 mm depth respectively (Figure 9-a-b).

In this experiment, we use a specialy designed two dimensional array. Indeed,this transducer has been built to overcome beam aberrations produced by the geometry of the liquid-solid interface. Such prefocused arrays have a focusing lens designed to make all the propagation times between the transducer surface and the focal point equal, thus providing optimum focusing at this point. This « Fermat » design array has two radius curvature, 600 mm (100 mm water path and 125 mm depth in titanium) and 250 mm for the other one. The elliptical aperture has two diameters, equal to 120 mm and 80 mm, and the theorical beam diameter at focal point is equal to 2.5 mm. The 121 piezoelectric elements are set out on six annuli, the central one is a plane disc and the others are annuli sector elements (Figure 9-c). A wide illuminating beam was transmitted by the nine central elements of the transducer. After the first illumination, the echo from the FBH was recorded and time-reversed by the four external annuli of the array. We have made two iterations (three shoots and two time-reversed processes) and we have selected a time reversal window of 2 μs wich corresponds to an inspection depth of 6 mm.

Results:

We present the signal to noise peak ratio (S/N), calculated with the results of the incoherent logarithmic summation (Table 1). All the FBH, located between 23 mm and 140 mm depth, were detected with a S/N peak between 12 and 27 dB except the 5 mm depth FBH. In fact, the transducer was designed to focus at 125 mm depth in titanium and the echo produced by the liquid-solid interface is long about 2.5 μs wich corresponds to a dead zone of 7.5 mm near the surface. The TRM performs in real time a Fermat surface matched to focus on the defect and the FBH is automatically detected in a section of more than 8 mm x 8 degrees around the 2-D Time Reversal Mirror axis.

These results demonstrate the ability of TRM to compensate the distortion induced by focusing at a different depth than the natural focal point of the array. In addition, the time reversal system doesn't require a perfect quality or geometry of the billet and no accurate adjustements.



(a) (b) (c)

Figure 9. Configuration of the billet experiment (a, b) and prefocussed geometry array

Table 1.: Results of the titanium billet test

Depth (mm)	S/Npeak (dB)
23	12
46	15
69	21
91	27
114	15
140	17

CONCLUSION

T.R.M. brings a real improvement in inspection of sample with high ultrasonic speckle noise level. All the experiments show the effectiveness and capabilities of the time reversal technique to locate defect within a sample with a plane or a complex interface. With this technique we improve the signal to noise ratio for two reasons. First, time reversal process is a self adaptive focusing technique which realizes a focused wave matched to the defect shape, to the propagation medium and to the geometry of the mirror and the medium. This ability of focusing increase the signal to noise ratio. Second, the time reversal process reduces the amplitude of the speckle noise. Due to the loss of information during the propagation the process cannot focus on microstructure whose dimension is small with respect to the wavelength. Using these properties of the time reversal process, we developed a new algorithm, the deviation histogram, able to distinguish during the inspection defect zone from speckle noise zone. This algorithm just needs to compare the received signals after one and two time reversal process.

We also demonstrated the ability of the time reversal process to detect defect located between 23 and 140 mm depth in a very noisy medium beneath a complex geometry interface. We used a special Fermat design array with 600 mm radius of curvature and working at 5 MHz. All the defects were detected with a signal to noise ratio higher than 12 dB. We can remark that the TRM achieves its best results in the billet center which is the most critical depth for the classical techniques due to the pollycristalline microstructure noise and the high attenuation level.

These performances (detection of small defect in a noisy background component, and through complex interfaces) show the potential of the time reversal process to be adapted and used for industrial problems.

REFERENCES

1. M. Fink, C. Prada, F. Wu, and D. Cassereau, Proc IEEE Ultrason. Symp. 1989, Montreal, PQ, Canada, vol.2, 1989, pp.681-686.
2. C. Prada, F. Wu, and M. Fink, J. Acoust. Soc. Amer., July 1991.
3. M. Fink, Ferroelec., IEEE Trans. Ultrason., Freq. Contr., vol. 39, n°5, September 1992.
4. F. Wu, J.L Thomas, and M. Fink, IEEE Trans. Ultrason. , Ferroelec., Freq. Contr., vol. 39, n°5, September 1992.
5. N. Chakroun, M. Fink, F. Wu, Proc IEEE Ultrason. Symp.1992, Tucson, U.S.A, vol.2, 1992, pp809-814.
6. S.W Flax, and M. O'Donnell, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. 35: 758-767 (1988).
7. N. Chakroun,V. Miette, M. Fink, F. Wu, « Ultrasonic inspection of titanium alloys with a Time Reversal Mirror », in this volume, 1994.