Mechanical Property Analysis with Ultrasonic Phased Array

Wen-Ai SONG [1], Ke-Yi YUAN [1], Yi-Fang CHEN [1], Hui-Ming YAN [2]

[1]Department of Mechanical Engineering, Tsinghua University

Beijing 100084, China;

Phone: +86-10-62773857, Fax: +86-10-62773862

Email: songwenai@nuc.edu.cn,

yky@mails.tsinghua.edu.cn, chenyifang@mail.tsinghua.edu.cn

[2]School of Information and Communication Engineering,

North University of China, Taiyuan 030051, China

Abstract

In titanium alloy specimen and optic glass specimen, the velocity of ultrasonic longitudinal wave, transverse wave and quasi-rayleigh wave are measured with phased array transducer and signal processing. Because the measurement of the echo's amplitude and phase is more accurate with phased array transducer than a single transducer, the measurement of the ultrasonic velocity is more accurate accordingly. The method proposed in this paper can also be used on the optic property evaluation of optic materials.

Key words mechanical property analysis, phased array, velocity of ultrasonic, signal processing, optic property evaluation

1. Introduction

It is well known that while the testing of material with ultrasound, the accurate measurement of the defect position and the defect shape is based on the accurate measuring to the velocity of the ultrasonic. And on the industrial production line, the mechanical property (e.g. the elastic modulus) measurement of the raw material and the products is very significant for three purposes, i.e. avoiding the useless machining with a defective material, improving the processing technics and ensuring the mechanical property of the product. The velocity of the ultrasonic in the solid material could reflect the mechanical property (e.g. the elastic modulus) directly[1][2][3]. Especially, the velocity of the ultrasonic in the optic glass could characterize the optic property qualitatively. So studying on the accurate measurement of the ultrasonic velocity in materials is very significant.

The more accurate the measurement of the ultrasonic velocity could be, the tinier mechanical property changing could be measured. Generally, the ultrasonic velocity in materials are measured with single transducer (echo method), or a pair of transducers (transmit method). Because the big receiver aperture using in these two methods, the signal received by different points on the transducer surface have different phase-delay, the signal received by the transducer is aberrated. That influenced the accuracy of the flight time measurement, and finally reflected in the accuracy of ultrasonic velocity measurement. Using the phased array transducer and signal processing, the aberration caused by the receiver aperture is corrected, and the accuracy of the ultrasonic velocity measurement is improved.

2. measurement of the elastic modulus

The velocity of longitudinal wave in a material is C_l, and the velocity of the transverse wave is C_s, the density is ρ, then the follow formulas could be used to calculated the elastic modulus[1]:

The poisson's ratio: $$\sigma = \frac{C_l^2 - 2C_s^2}{2(C_l^2 - C_s^2)} \quad (1)$$

The shear modulus: $$G = \rho C_s^2 \quad (2)$$

The Young's modulus: $$E = \rho C_s^2 \frac{3C_l^2 - 4C_s^2}{C_l^2 - C_s^2} \quad (3)$$

The bulk modulus: $$K = \rho(C_l^2 - \frac{4}{3}C_s^2) \quad (4)$$

According to the formulas above, if C_l, C_s and ρ is measured, the elastic modulus could be calculated. If the velocity is dynamic, then the dynamic elastic modulus could be measured. If the distribution of the velocity is measured, the mechanical property difference between different areas of the material could be analyzed. So the measurement of the ultrasonic velocity is both the basic technology and the key technology of the mechanical property analysis with ultrasonic.

So far, using phased array and signal processing measured the velocity of the ultrasonic is still a new direction, in this paper a method about this is proposed.

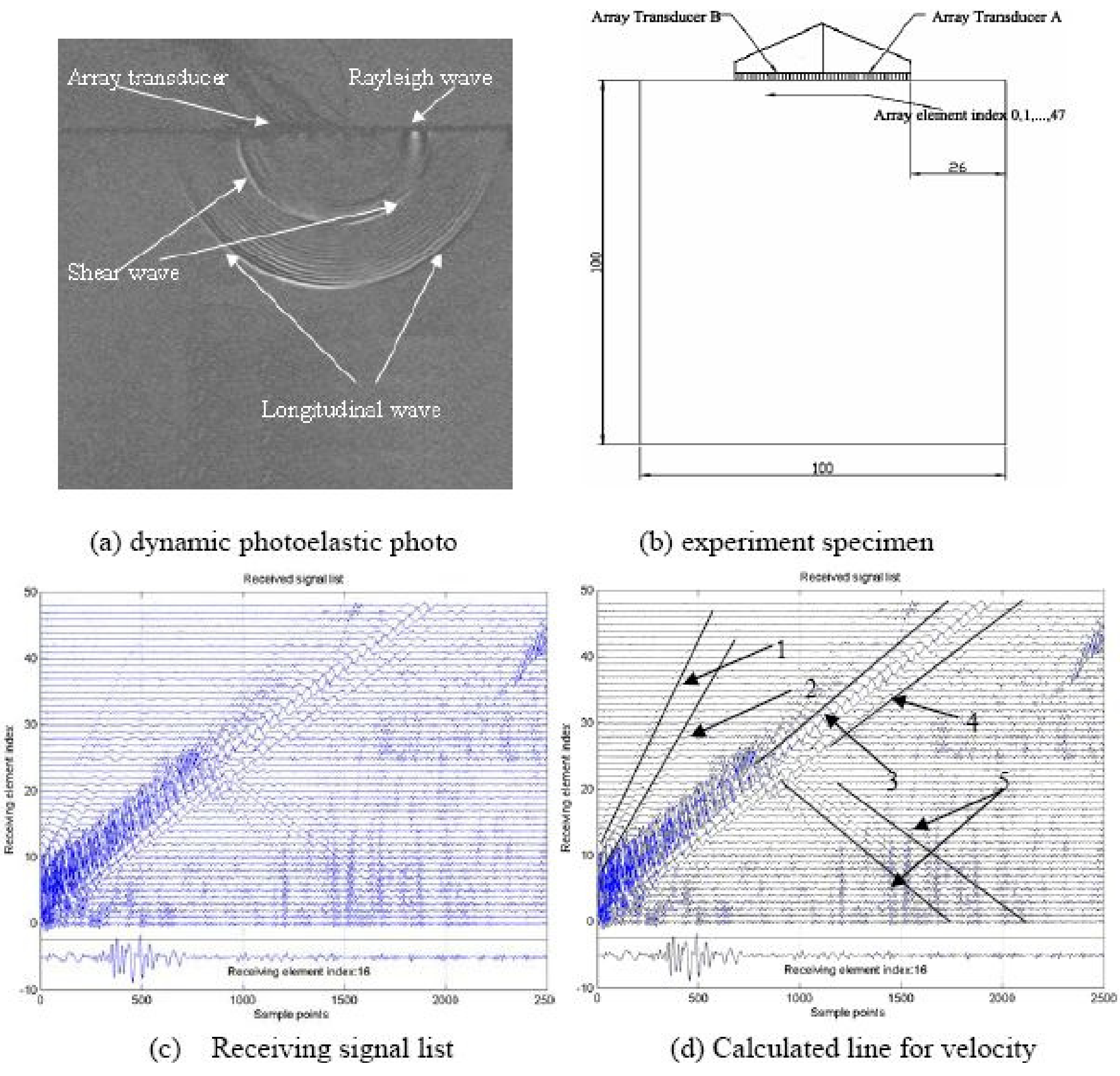
3. Measuring the velocity of the ultrasonic transmitting on the surface

With the surface wave, the surface stress, surface hardness of a material could be measured; and also could the elastic modulus of film materials and homogeneous materials be measured. Measuring surface wave velocity with array transducer, the transducer could be set at the aimed position, the an element of the transducer emitted, all the elements received, from the receiving signal list, the velocity of the surface longitudinal wave, the surface transverse wave and the quasi-rayleigh wave could measure intuitively. Then the mechanical property could be analyzed.

Principle of the measurement is shown in figure 1. The dynamic photoelastic photo (figure1 (a)) showed that while an element of the array transducer was emitting, there are longitudinal wave and transverse wave transmitting on the surface with the respective velocity in the specimen, and there is quasi-rayleigh wave behind the surface transverse wave. Accordingly, while an element of the array transducer was emitting, and all the elements were receiving, from the receiving signal the three velocities could be measured.

The specimen detected is shown in figure 1 (b). Two linear array transducers are set as in the figure. Each transducer has 24 elements. The element's size is $1mm \times 20mm$, frequency is 6.25 MHz. The elements are indexed as shown in the figure, i.e. $0, 1, \Lambda, 47$. The thickness of the specimen is $20mm$.

While the element 0 is emitting, and all the elements are receiving, the signal list is shown in figure 1 (c). The x axis is sample points, and the y axis is the receiving element index. In the figure1 (d), the velocity calculating lines for different type ultrasonic wave are indicated. The velocity calculating line is based on the signal list (figure1(c)), and its slope ratio is the velocity of the corresponding ultrasonic. In the figure, 1 indicates the longitudinal wave on the surface, 2 is the longitudinal wave in the transducer, 3 is the transverse wave on the surface, 4 is the quasi-rayleigh wave, 5 is the echoes reflect by the interface between the two transducers.



(a) dynamic photoelastic photo (b) experiment specimen

(c) Receiving signal list (d) Calculated line for velocity

Figure 1. Principle of surface wave velocity measurement and specimen for experiments

Signal processing: generally, using linear array transducer with N elements, while the element i is emitting, and all the elements are receiving, there are N wave series could be received, recorded as follow:

Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen. (5)

W_i is the receiving signal list while the emitter is element i, the upper of figure 1(c) is shown the receiving signal list W_0. $w_{ij}(n), i, j = 0,1,,2,\Lambda\ N-1; n = 0,1,2,\Lambda\ ,M-1$ is the signal received by element j while the emitter is i, M is the amount of sample points. The lower of figure 1(c) is shown the receiving signal $w_{0016}(2500)$.

Using figure 1(d), approximate velocity of different type ultrasonic wave could be estimated, i.e. the slope ratio of the calculating line. The velocity of longitudinal wave is recorded as C_{l0}, velocity of transverse wave is recorded as C_{s0}, and velocity of quasi-rayleigh wave is C_{r0}. Then using the approximate velocity, the signal could be selected as follows:

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$win_{ij}(n)$ is a selecting window function, center point is l_{ij}, length is $2l$. And,

$$l_{ij} = INT(t_{ij} / \Delta t) \qquad t_{ij} = \frac{(j-i)\Delta d}{C_0} \tag{7}$$

l could be set as

$$l = INT\left(\lambda / (C_0 \Delta t)\right) \tag{8}$$

$INT(\bullet)$ is the rounded function. C_0 is the velocity of the ultrasonic, and $C_0 = C_{l0}$, $C_0 = C_{s0}$, $C_0 = C_{r0}$, respectively. Δd is the center distance between the two neighbor elements, Δt is the time sampling interval, and λ is the wavelength while $C_0 = C_{l0}$, $C_0 = C_{s0}$, $C_0 = C_{r0}$, correspondingly.

According to the actual situation, different window function could be changed. In this paper, the follow window function is used:

$$win_{ij}(n) = \begin{cases} 1 & l_{ij} - l \le n \le l_{ij} + l) \\ 0 & others \end{cases} \tag{9}$$

Having the correlation processing between $w^1{}_{0j}(n)$ and $w^1{}_{01}(n)$, picking the maximum sample points, calculating the delay from 1 to j, record as $\Delta t_{0j}, (j = 2,3,\Lambda\ , N-1)$, then the velocity is:

$$C_j = (j-1)\Delta d / \left|\Delta t_{0j}\right| \tag{10}$$

$$C = \frac{\sum_{j=2}^{N-1} C_j}{N-2} \tag{11}$$

While $C_0 = C_{l0}$, $C = C_l$; $C_0 = C_{s0}$ for $C = C_s$; and $C_0 = C_{r0}$ for $C = C_r$. The experiments results are shown in table 1.

Table 1 Measurement of Surface wave velocity

Material	C_l	C_s	C_r
Titanium alloy	$6330 m/s$	$3210 m/s$	$2750 m/s$
K9 optic glass	$5980 m/s$	$3620 m/s$	$2930 m/s$

Under the situation that the element size $1mm \times 20mm$, and frequency is 6MHz, the effective digital of the velocity is 3, if the measuring resolution of the center distance between the two neighbor elements is higher, more effective digitals could be got.

4. Velocity of ultrasonic inside the specimen

The signal process is similar to those described above. Assumed that inside the specimen, there is a scattering point $p(x,y)$, then in formula (7), l_{ij} is changed to:

$$l_{ij} = INT(t_{ij} / \Delta t) \qquad t_{ij} = \frac{r_i + r_j}{C_0} \tag{12}$$

r_i and r_j is the distance between the scattering point $p(x,y)$ and element i and j respectively.

Having the correlation processing between $w_{ij}^1(n)$ and $w_{ii}^1(n)$, picking the maximum sample points, calculating the delay $\Delta t_{ij}(i, j = 0,1,2,3,\Lambda, N-1, \quad i \neq j)$, and then dealing with W_i:

$$W_i^1(n) = \sum_{\substack{j=0 \\ j \neq i}}^{N-1} w_{ij}^1(n + \Delta l_{ij}) \tag{13}$$

$$\Delta l_{ij} = INT(\Delta t_{ij} / \Delta t) \tag{14}$$

And having the correlation processing between $W_i^1(n)$ and $W_0^1(n)$, get the delay $\Delta t_i (i = 1,2,3,\Lambda, N-1)$, then the velocity is:

$$C_i = i\Delta d / |\Delta t_i| \tag{15}$$

$$C = \frac{\sum_{i=1}^{N-1} C_i}{N-1} \tag{16}$$

While $C_0 = C_{l0}$, $C = C_l$; $C_0 = C_{s0}$ for $C = C_s$; and $C_0 = C_{r0}$ for $C = C_r$.

5. Comparison experiment between phased array and single transducer

The serial single rectangle transducers' parameters, the length is $20mm$, width changing from $1mm$ to $20mm$. The linear array transducer has 20 elements, and the size of the elements is $1 \times 20mm$. The frequency of all the transducer is 6.25MHz. With the titanium alloy specimen showed in figure 1(b), using all the transducers to measure the velocity the longitudinal wave. While using the array transducer, the signal processing is used. The results are in table 2.

Table 2 Comparison between phased array and single transducer

Width of transducer (mm)	1	2	5	6	10
$C_l\,(m/s)$	6252.4	6252.2	6253.4	6252.7	6250.9
Width of transducer (mm)	13	15	19	20	array
$C_l\,(m/s)$	6250.2	6249.8	6248.3	6247.9	6272.0

For both of the amplitude and the phase would be corrected with phased array transducer and signal processing, so the signal from the array transducer is much batter than that from the signal transducer. Figure 2 shows the signal from the array transducer and single from transducers of different width.

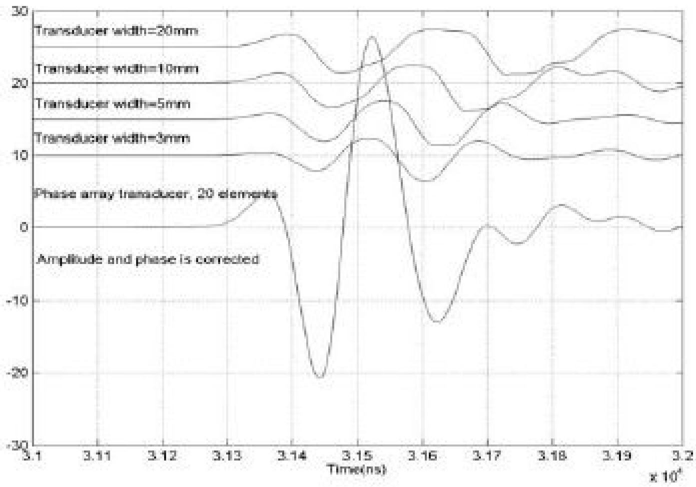
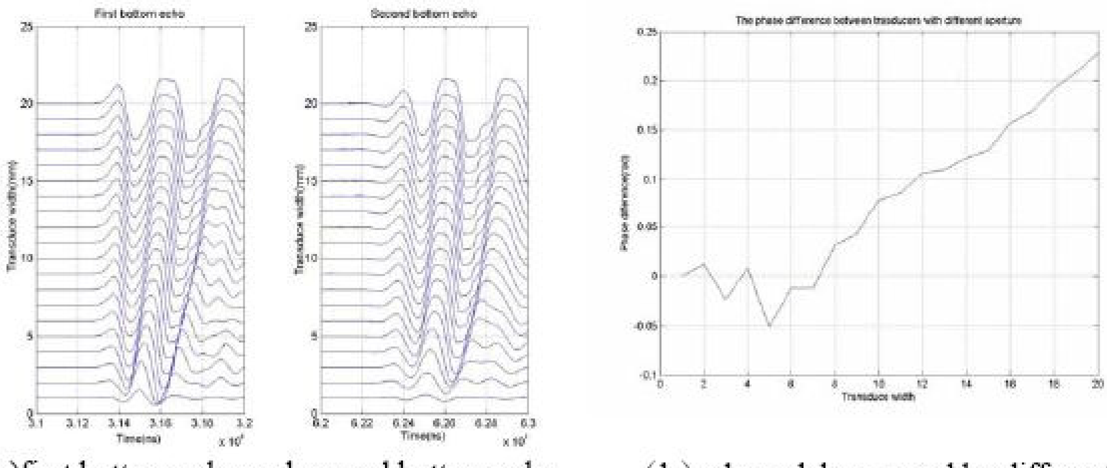


Figure 2. signal from array transducer and from transducers of different width

Figure 3 showed the first bottom echo signal and second bottom echo signal using single transducers of different width. The x axis is flight time, and the y axis is the width of the transducer. While the aperture increased, the phase of the receiving signal delayed more sample points, the increasing of amplitude is not very clearly, and the signal is distorted worse. The phase delay between the first bottom echo and the second bottom echo is calculated by correlation analysis. And the phase delay-aperture curve is showed in figure 3 (b), the x axis is the width of the transducer, unit is mm, and the y axis is phase delay between the first bottom echo and the second bottom echo, unit is rad. While the width of the transducer is $5mm$, the phase delay got the minimum. After that point, the phase delay is increased with the increasing of the width of the transducer.



(a)first bottom echo and second bottom echo of transducers with different aperture

（b） phase delay caused by different transducer aperture

Figure 3. Measurement error caused by transducer aperture

6. Conclusions

From the experiment result in figure3, it could be conclude that, while the width of the transducer is $1mm$, amplitude of the receiving signal is small, and the phase measurement of this signal is not accurate enough. The same error exists on the second bottom echo of $2mm$ width transducer. As the aperture increased, the receiving signal is distorted worse, that would add error to the flight time measurement. So the measurement of the ultrasonic velocity with single transducer in different material in different size, the aperture of the transducer need to be chose suitably.

As the error caused by the transducer aperture in the measuring of flight time is about $100ns$, even the transmit distance of the ultrasonic could be measured up to six effective digitals, the velocity only could got three effective digitals, because the time measuring error is not small enough. This fact can be checked in table 2. While the array transducer and the signal processing is used, as the phase delay, and amplitude distorted is corrected by this method, the resolution of the flight time measurement is up to $1ns$, then the velocity could get more than four effective digitals.

For the phased array method can corrected the phase and the amplitude of the signal, and can change the aperture flexibly, with this method, the measuring to the velocity of the ultrasonic could be more accuracy. And as the phased array method has a statistical average effect on the signal, the amplitude ratio between the two bottom echoes could well reflect the average attenuation of the material. Using this method, the accuracy of the measurement of the transverse wave velocity could be better too, and then the measurement of the elastic modulus could be more accurate.

While using the dynamic photoelastic equipment to prove the principle of this method, another phenomenon is noticed, that the optic glass with different acoustic impendence, had different optic property. So with the ultrasonic velocity in the optic glass, the optic property of it could be estimated qualitatively. The quantitative relation between these two parameters is need to a deeper study.

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