MEASUREMENT OF REFLECTANCE FUNCTION FOR LAYERED STRUCTURES USING FOCUSED ACOUSTIC WAVES

W.-J. Xu and M. Ourak
Institut d'Electronique et de Microelectronique du Nord
Departement Opto-Acousto-Electronique (UMR CNRS 9929)
Universite de Valenciennes, B.P. 311, 59304 Valenciennes, France

INTRODUCTION

In the ultrasonic NDE of layered materials and structures, such as bonded joint, coating, and in particular the composite material, the surface or Lamb wave velocity or the reflection and transmission coefficient are measured, to determine for examples, the elastic constants, the anisotropy and the integrity of the materials, etc. A commonly used technique to determine locally the surface or Lamb wave velocity V_g is based on the measurement of the reflection minima or the transmission maxima at oblique incidence of the test sample. It is supposed that at the critical incident angle θ_c where the reflection coefficient appears the minima, the surface or Lamb waves are favorably generated and $V_g=V_0/\sin\theta_c$ where V_0 is the wave speed in coupling liquid. So, the determination of the reflection function is essential and important. In general, the acoustic reflection or transmission coefficient of a layered medium depends on the wave incident angle θ, the wave frequency f, and the orientation angle ϕ if the material is anisotropic. To obtain the whole information of this reflectance function $R(\theta,\phi,f)$, one needs to insonify the structure at varying incident and orientation angles and do the frequency spectroscopy using the wide-band transducer.

There exist several experimental techniques to evaluate the reflection function. One is the traditional pitch-catch method [1-3] where two identical transducers are disposed at the symmetrical angles with respect to the normal incidence of the sample. A goniometer system is necessary for the adjustment of the two transducers at a varying incident-reflection angle in order to get the angular dependent reflection coefficient. Another one is the double through transmission method [4-5]. This method employs only one single transducer served as the transmitter and the receptor with an acoustic reflector placed at the transmission side of the sample. The goniometer is also needed for the rotation of the test sample. An improved method recently proposed is the double reflection method [6]. The reflector is attached at the same side of the transducer. This is useful in the situation where the transmission side is not accessible. In all these methods, however, a great inconvenience is the use of the goniometer system for an accurate angular adjustment of the transducer or the sample. The use of such system is not very practical in industry situations. Another problem is that with the finite-sized transducer where the incident wave is not really a plane one, there will take place the nonspecular reflection at the critical angles. This phenomenon will complicate the profile of the reflection beam and can perturb the measurement results.

To overcome these inconveniences, we consider a focused wave method to evaluate the reflectance function for layered materials. Owing to the great angular aperture of the focus transducer, the layered plate is insonified by an acoustic beam covering a great incidence spectrum. The reflection information at these different incident angles can be obtained at the same time instead of doing the angular scanning. The principle of this method is based on the measurement of the acoustic material signature AMS or the so called *V(z)* function. An Fourier transform based inversion algorithm permits to obtain the reflectance function from complex measured *V(z)* response. This technique greatly simplifies the experimental procedure compared to conventional ones using the goniometer. In this paper, the example result is given for a unidirectional fiber composite plate.

V(Z) METHOD AND ITS INVERSION

The inversion algorithm to obtain the reflectance function from *V(z)* response is recalled briefly as follows [7-8]:

When an acoustic lens or a focus shell transducer is placed at the normal incidence of a test sample (weather the sample is a substrate or a layered one), with the tone burst wave excitation, the received signal corresponding to the first reflection echo can be expressed as

$$V = \int_{-\infty}^{+\infty} G(k_r)U^+(k_r)U^-(k_r)R(k_r)\exp(-2jz\sqrt{k_0^2 - k_r^2})dk_r \qquad (1)$$

where $k_r = k_0 \sin\theta$ (2)

k_0 is the wave number in coupling liquid and θ the incident angle, $U^+(k_r)$ and $U^-(k_r)$ are the pupil functions of the lens in direct and inverse direction respectively, $R(k_r)$ is the global reflectance function of the sample, z is the normal distance from the sample surface to the lens focus plan, $G(k_r)=1$ if the lens is line focus one and $G(k_r)=2\pi k_r$ if the lens is point focus one. When the lens is mechanically translated in z direction, the varied V with z is the so called *V(z)* response. In general, *V(z)* is a complex signal in which the tone burst amplitude is its magnitude and the relative delay of the sinus oscillation in the burst corresponds to its phase. To obtain the reflectance function $R(k_r)$ from *V(z)* inversion, the integral variable k_r is changed by

$$p = \frac{1}{\pi}\sqrt{k_0^2 - k_r^2} \qquad (3)$$

then equation (1) becomes

$$V(z)=\int_0^{\frac{k_0}{\pi}} U(p)R(p)\exp(-2\pi jzp)dp \tag{4}$$

and equation (4) is simply the Fourier integral of the multiplication of the sample reflectance function $R(p)$ with a function $U(p)$ which depends only on the lens or transducer characteristics. Suppose that $V(z)$ is obtained for a layered sample having reflectance function $R(p)$ and $V_g(z)$ is obtained for an acoustic reflector having the unity reflectance function using the same lens or transducer, the sample reflectance function $R(p)$ can be then determined by the normalized inverse Fourier transform between $V(z)$ and $V_g(z)$ as

$$R(p)=\frac{F^{-1}\{V(z)\}}{F^{-1}\{V_g(z)\}} \tag{5}$$

where F^{-1} represents the inverse Fourier transform operation. Combined with the frequency scanning or (and) the orientation angle ϕ scanning for anisotropic material and note from equation (3) that $p=(k_0/\pi)\cos\theta$, the multi-variable reflectance function can be reconstructed by

$$R'(\theta,\phi,f)=R(\frac{k_0}{\pi}\cos\theta,\phi,f)=\frac{F_z^{-1}\{V(z,\phi,f)\}}{F_z^{-1}\{V_g(z,\phi,f)\}} \tag{6}$$

EXPERIMENTAL SETUP

The experimental setup is simple and its block diagram is shown in figure 1. A stepping motor driver realizes the mechanical translation of the transducer in z. If the material is anisotropic, a rotation motor in ϕ is employed to drive the line focus transducer around its axis. A function generator delivers the emission signal for transducer excitation. A digital oscilloscope performs the acquisition of the received signal. A personal computer commands the system via a GPIB bus and store the acquired signals into data files for post treatment.

A general purpose software is used for scanning and signal acquisition. The programmed panel (shown in the below of Figure 1) is developed in MATLAB via a MEX interface file to access the GPIB communication. In the control panel there are up to four scan axes. Either of the axes can be connected to a stepping motor driver or a function generator for mechanical or frequency scanning. There is no limit for the type of the scan apparatus and the oscilloscope so long as a connecting program written in MATLAB is added for each special apparatus. After selecting the scan axes and setting the scan length and step, the signal sampled at a selected oscilloscope channel is registered at each scanning step. As the $V(z)$ signal is a complex one, in tone burst working mode, the amplitude and the delay for a designated sine in the reflection echo are searched to get respectively the magnitude and the phase information. In implusion working mode, the complex measurement can be simply obtained from the frequency spectrum of the signal.

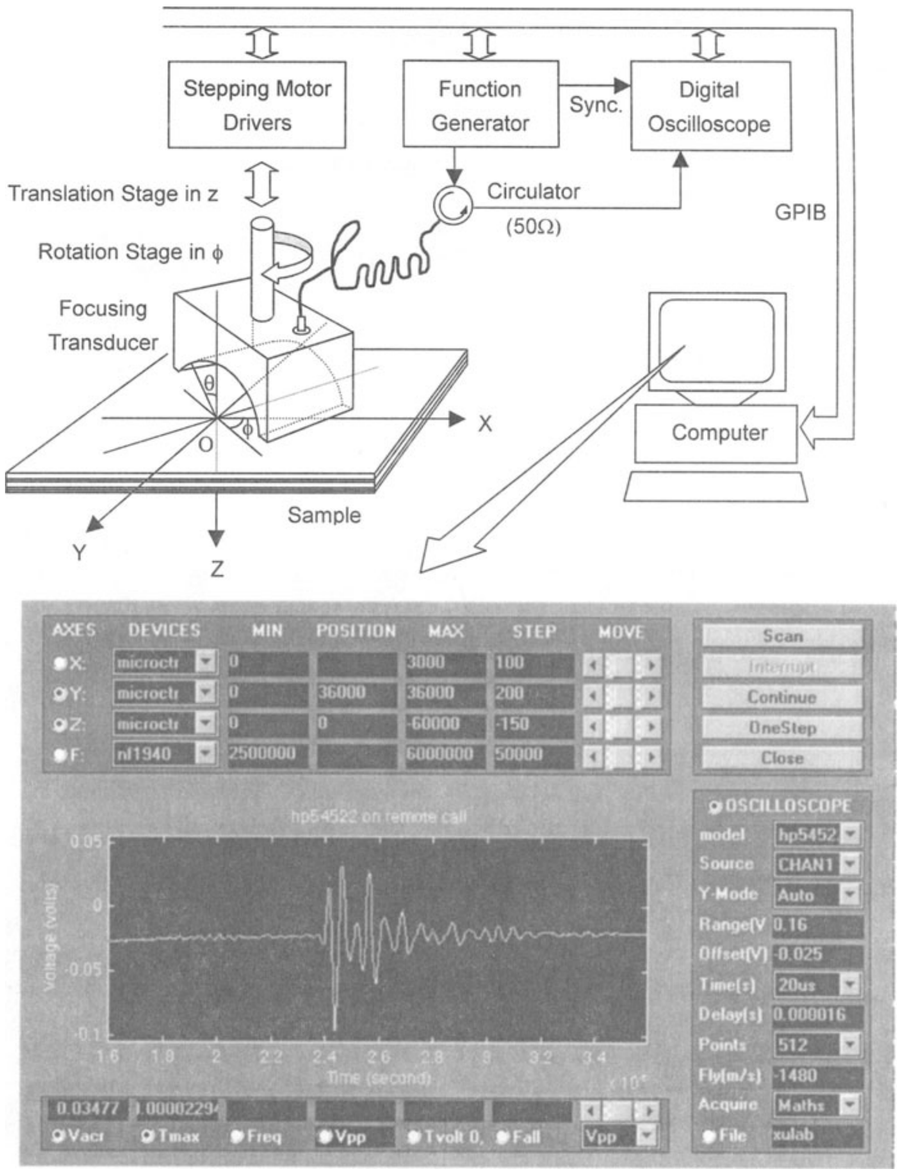


Figure 1. Experimental setup and acquisition panel developed in MATLAB 4.2c

RESULTS FOR A COMPOSITE PLATE

A 2mm thickness and unidirectional fiber reinforced composite plate is used as a testing sample for its $R(\theta,\phi)$ reflectance function reconstruction. A two dimensional $V(z,\phi)$ scan is realized for this sample using a line focus transducer at 2 MHz frequency (transducer characteristics: geometrical radius = 30mm; width = 45mm; angular aperture = $\pm 45°$). The transducer response $V_g(z)$ is obtained for an acoustic reflector formed by a very thin plastic film with air-charged backing. As the $V_g(z)$ response is independent of the orientation angle ϕ, only one dimensional z scan is necessary. The scanned complex data are presented in figure 2. The intention of the magnitude (Fig.2-a) and the phase (Fig.2-b) are represented in a relative gray level image with a $V(\phi)$ profile at a fixed z value and a $V(z)$ profile at a fixed ϕ value.

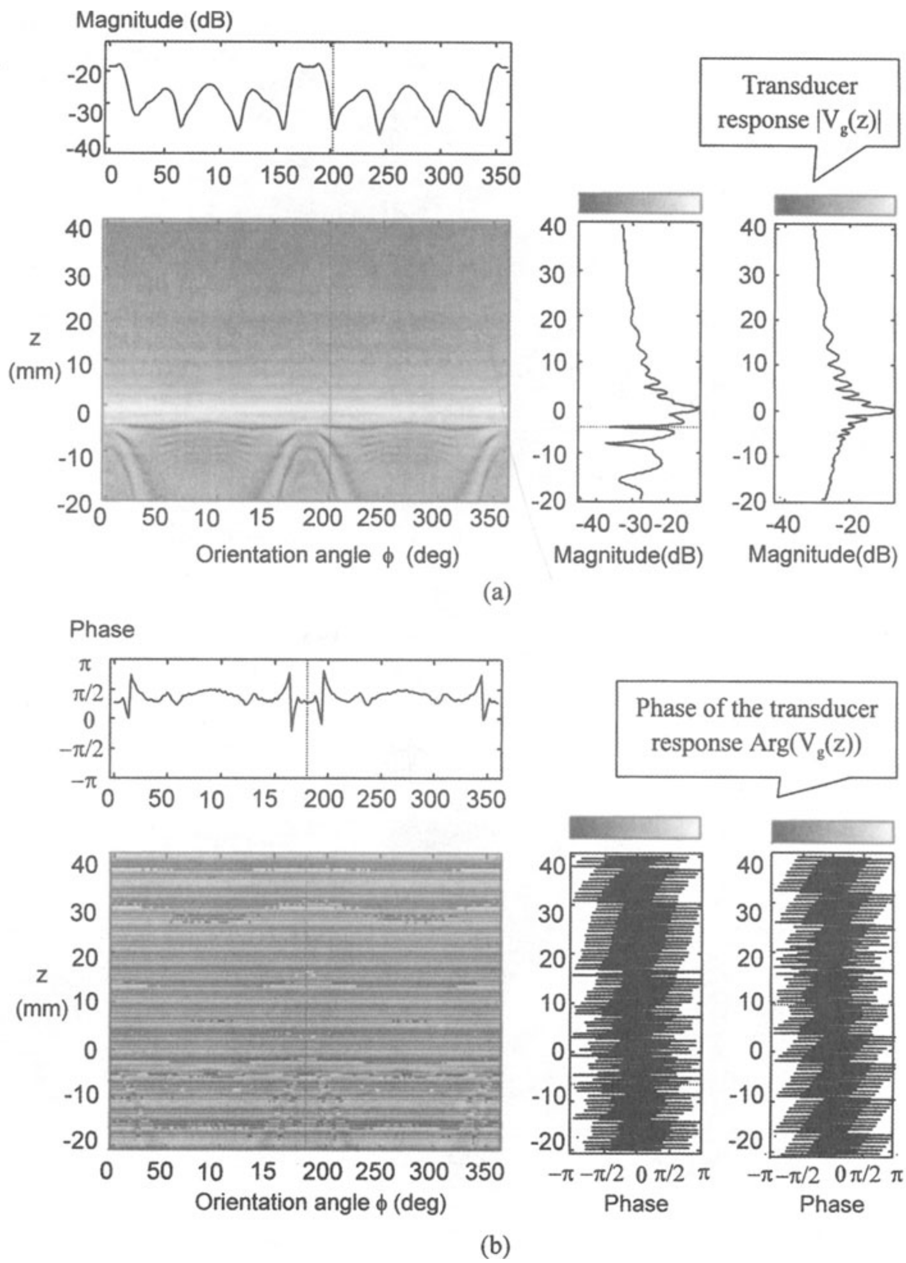


Figure 2. $V(z, \phi)$ scan data for a 2mm thickness fiber reinforced composite plate at 2 MHz (a) Magnitude image (b) Phase image

The first step of the inversion is to apply the inverse Fourier transform to the original scanned $V(z,\phi)$ in z for each ϕ. The transformed sample response and the transformed transducer response are presented in figure 3. After the transformation, the vertical coordinate of the image becomes the incident angle θ instead of the distance z. The second step of the inversion is simply to divide the transformed sample response $V(\theta,\phi)$ by the

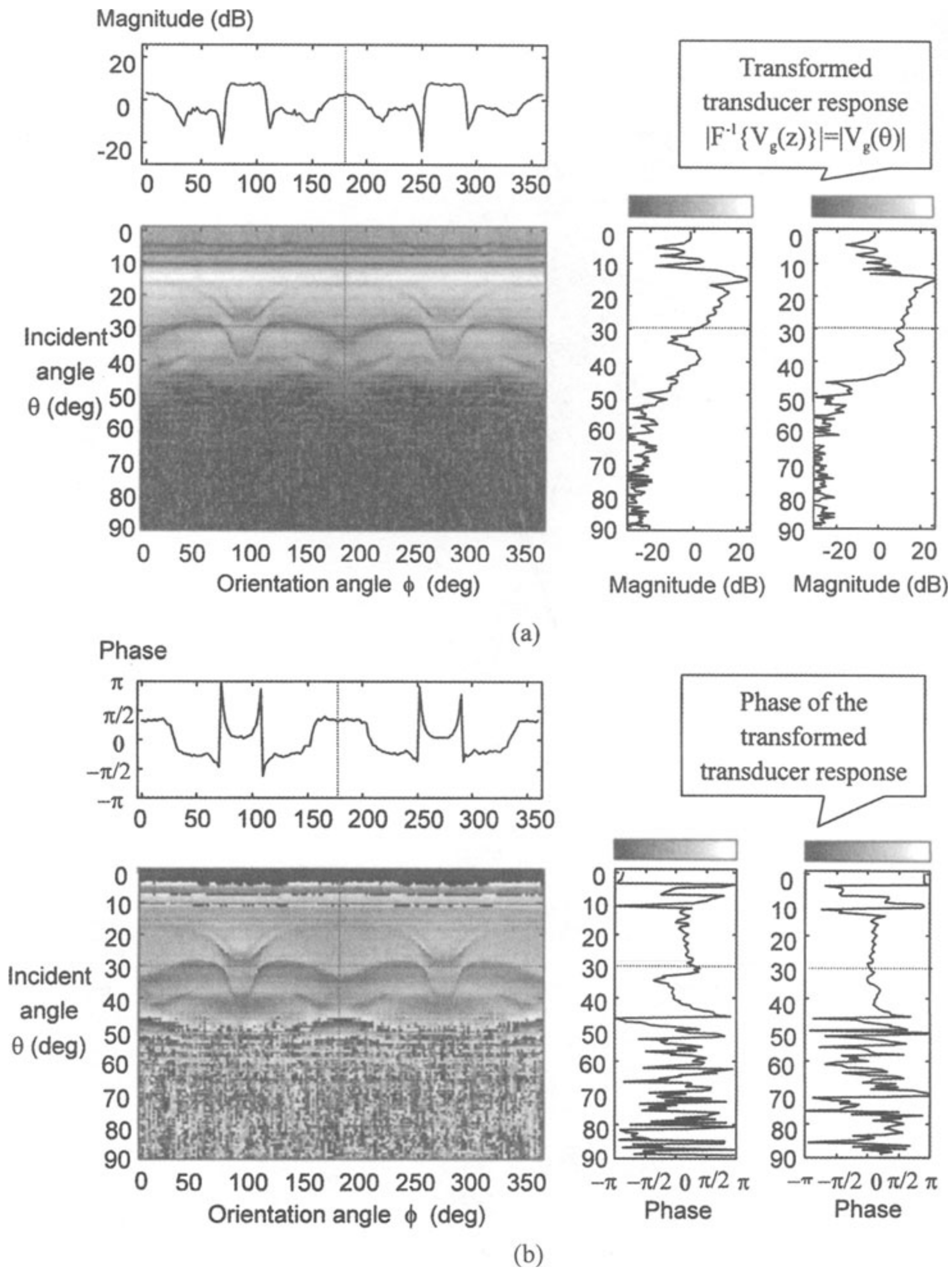
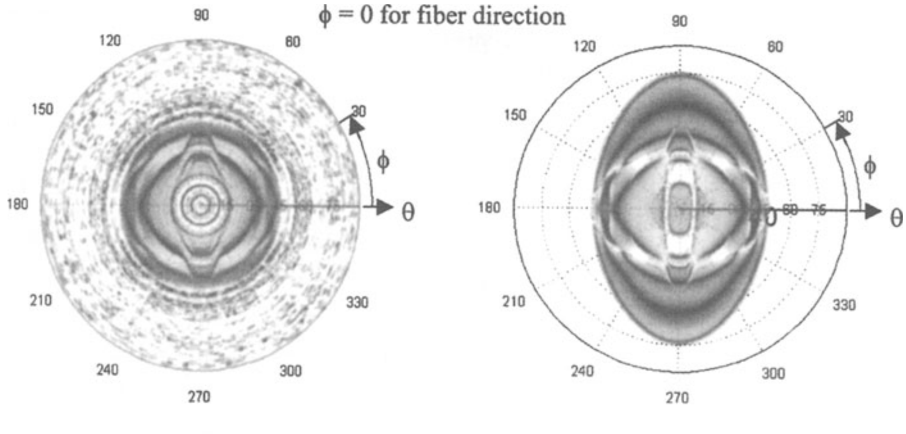
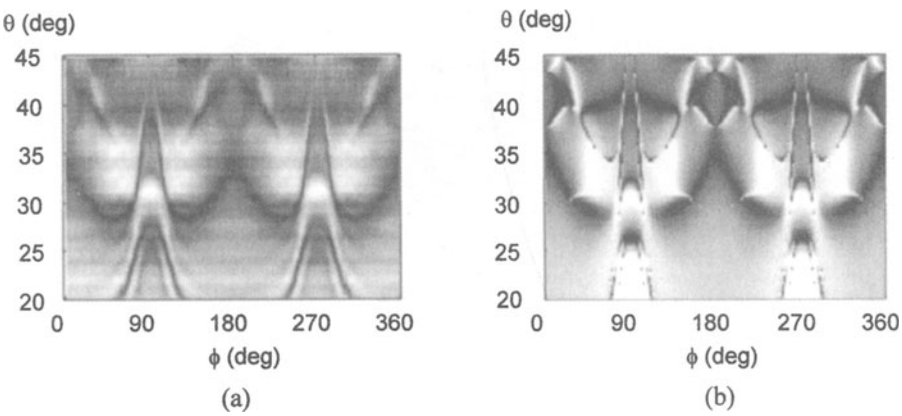


Figure 3. Inverse Fourier transformed $V(\theta,\phi)$ data (a) Magnitude image (b) Phase image



(a) (b)

Figure 4. (a) Inverted reflectance function $R(\theta,\phi)$, (b) Theoretically calculated reflectance function $R(\theta,\phi)$



(a) (b)

Figure 5. Reflectance function $R(\theta,\phi)$ for θ = [20 45] and ϕ = [0 360], (a) Inverted one (b) Calculated one.

transformed transducer response $V_g(\theta)$ for each orientation angle ϕ. The transformed $V(\theta,\phi)$ function corresponds in fact to the angular spectrum of the reflected field at different orientation angle ϕ of the sample. For the transformed transducer response, the $V_g(\theta)$ is the angular spectrum of the transducer's emission field.

The final inversion result is presented under polar coordinate in figure 4-a. For comparison, the theoretical prediction of the reflectance function is given in figure 4-b (where the material's elastic constants used for calculation are (in $10^{10}N/m^2$) c_{11}=12.59, $c_{12}=c_{13}$=0.55, c_{23}=0.63, $c_{22}=c_{33}$=1.35, $c_{44}=(c_{22}-c_{23})/2$, $c_{55}=c_{66}$=0.62, ρ=1577 kg/m^3). Some remarks can be given as follows. As the used transducer has an angular aperture of 45 degree, only inferior to this maximum incident angle that the composite plate is effectively excited. Beyond this angle, there is too little incident energy. The signal to noise ratio is not sufficient enough to get the inversion function. Below 45 degree, the inversion result is excellent. However, when the incident angle goes down to 15 degree, the inverted reflectance function is degraded. This degradation is also due to a transducer defect that it has a poor emission field for incidence inferior to 15 degree (as can be seen from its field angular spectrum $|V_g(\theta)|$ in figure 3-a). To show more clearly the inverted reflectance function, the same result is presented in figure 5 for incident angle ranging from 20 to 45 degree. The contrast in the theoretically predicted function is much sharp than the measured one. This is certainly because that the wave attenuation in the material has not been taken into account for calculation.

CONCLUSION

A focused wave or $V(z)$ method is used to measure the complex reflectance function $R(\theta,\phi,f)$ of layered anisotropic materials. The experimental procedure is greatly simplified and rapid compared to the conventional ultrasonic methods using a goniometer. The future work includes the reconstruction of the complex elastic constants from the complete information reflectance function.

REFERENCES

1. T. Pialucha *et al*, J. Acoust. Soc. Am. 96 (3), 1651-1660, (1984).
2. D. E. Chimenti and A. H. Nayfeh, J. Acoust. Soc. Am. 83 (5), 1736-1743, (1988).
3. Y. Bar-Cohen *et al*, in *Review of Progress in Quantitative NDE*, Vol. 17B, pp. 1171-1176.
4. P. B, Nagy and L. Adler, J. Appl, Phys. 66 (10), pp. 4658-4663, (1989).
5. B. Hosten et al, in *Review of Progress in Quantitative NDE*, Vol. 17B, pp. 1117-1124.
6. K. Kawashima *et al*, in *Review of Progress in Quantitative NDE*, Vol. 17B, pp.1125-1130
7. K. K. Liang *et al*, IEEE Trans. Sonics Ultras. SU-32 (2), pp. 189-211, (1985).
8. W.-J. Xu and M. Ourak, NDT & E International 30 (2), pp. 75-83, (1997).