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The British Institute of Non-Destructive Testing
Newton Building, St George's Avenue, Northampton NN2 6JB, England
Telephone: Northampton +44 (0)1604 89 3811 Fax: +44 (0)1604 89 3861

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Development of high-precision ultrasonic microscopy measurement system and measurement of the surface wave velocities of (100) silicon wafer

Song Guorong, Lu Yan, Gao Zhongyang, Liu Yanli, Guo Yinghui, He Cunfu and Wu Bin

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A high-precision ultrasonic microscopy measurement system was developed in order to non-destructively test the mechanical properties of metal sheet and coating materials. The whole system is based on acoustic microscopy techniques. The ultrasonic waves are excited and received by a line-focus transducer. This paper presents the principles and methods of the surface wave velocity measurements using this system. The surface wave velocity is measured along different propagation directions on a (100) silicon wafer. The results of the measurement have good repeatability and consistency in the symmetry directions. They indicate that the system shows high accuracy and fine stability at defocusing positions and rotation angles. The system meets the measurement requirements for isotropic and anisotropic materials. In addition, this acoustic characterisation method can be used to measure the wave velocity at different frequencies, so the dispersion curves of the sheet metal and coating specimen can be measured by this method. As a result, the mechanical properties of the materials can be calculated by fitting the theoretical and experimental dispersion curves.

Keywords: Acoustic microscopy technology, lensless focus ultrasonic transducer, dispersion curves, mechanical properties, NDT.

1. Introduction

For conventional materials, traditional testing methods of the mechanical properties meet most practical needs. However, when measuring the performance of new materials and structures, such as nano-materials, amorphous materials, anisotropic materials, sheet metal and coating materials etc, the mechanical properties are difficult to evaluate due to their particular size and formation. The development of new measurement methods is an area of intense focus for international scholars[1-5]. An ultrasonic system based on acoustic microscopy has been previously developed by Guorong's team for non-destructive testing of the elastic constants of bulk small-size materials. This system has enabled the measurement of a variety of mechanical properties (elastic constants)[6-9], but the acoustic properties of sheet metal and coatings are extracted differently from those of bulk small-size materials. Thus, the measurement method is also different. To this end, the original system needed to be improved in movement accuracy and characterisation methods.

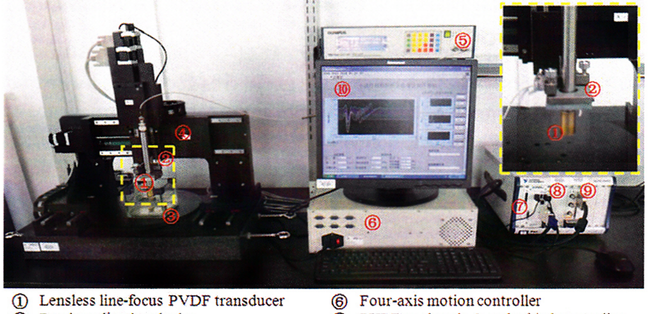
Song Guorong, Lu Yan, Gao Zhongyang, Liu Yanli, Guo Yinghui, He Cunfu and Wu Bin are with the College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, China. Tel: +86 10 67391720; Email: grsong@bjut.edu.cn

In this paper, a high-precision ultrasonic microscopy measurement system is developed and the $V(f, z)$ analysis method is used to measure the dispersion curves of wave velocity. The surface wave velocities of silicon wafer are measured along different propagation directions from 0° to 360°.

2. The measurement system

As is commonly known, an acoustic microscope utilises acoustic wave propagation characteristics to study the mechanical properties of the target specimen[10-14]. That is to say that the echo signal contains the interaction between high-frequency acoustic waves and the specimen; thus, mechanical properties are characterised by measuring the acoustic wave velocity.

A high-precision ultrasonic microscopy measurement system has been developed, based on $V(f, z)$ analysis techniques. This high-precision ultrasonic microscopy measurement system includes an embedded controller, a motion control device, a high-speed digitiser, a four-axis precise moving stage, a four-axis motion controller, an ultrasonic pulse receiver, a lensless line-focus PVDF transducer, a precise adjusting device for the transducer and a water tank. All equipment is shown Figure 1.



① Lensless line-focus PVDF transducer
② Precise adjusting device
③ Specimen & sink
④ Four-axis precise moving mechanism
⑤ Ultrasonic pulse generator-receiver
⑥ Four-axis motion controller
⑦ PXI-Bus chassis & embedded controller
⑧ High-speed digitiser
⑨ Motion control card
⑩ LCD monitor

Figure 1. Precision ultrasonic microscopy measurement system

The schematic diagram of this system is shown in Figure 2. Ultrasonic waves are generated and received by a lensless focus transducer. The focus transducer is installed on the z-axis. The specimen is placed into the tank on the turntable. The defocus distance between the transducer and the specimen is changed by moving along the z-axis, and the echo signals are measured at different defocus distances.

For a high-precision ultrasonic microscopy measurement system, the ultrasonic transducers can be categorised into two types: point-focus and line-focus transducers. These can be selected according to different test requirements and different types of materials. Figure 3 shows the lensless PVDF line-focus ultrasonic transducer.

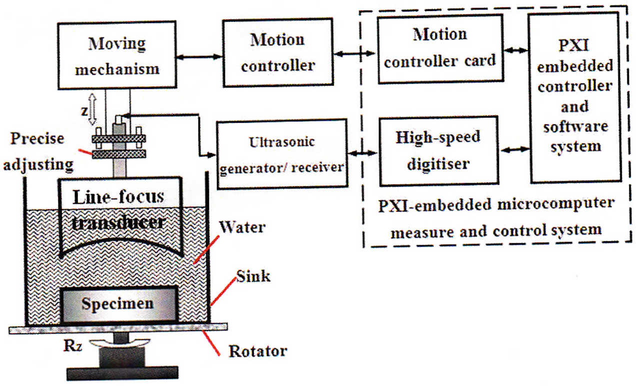


Figure 2. Block diagram of ultrasonic measurement system

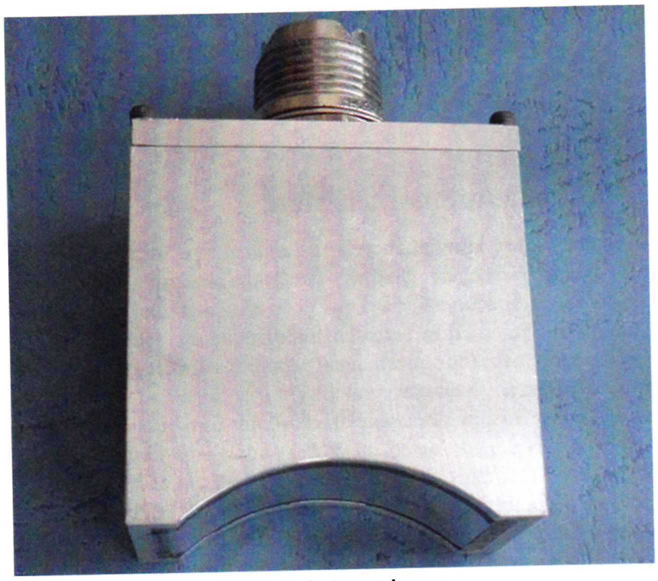


Figure 3. Line-focus ultrasonic transducer

3. Measuring principle and method of surface wave velocity

The propagation of the acoustic wave excited and received by a line-focus ultrasonic transducer is shown in Figure 4. This transducer's focal length is F and the half-angle is greater than the Rayleigh angle[15]. When the acoustic waves are excited by the transducer on the focal plane, which is the upper surface of the test specimen ($z = 0$), the transducer can only receive the direct reflection echo signal D from the surface of the test specimen. With the transducer moving downwards, the focal plane shifts from the upper surface of the test specimen ($z > 0$) and the acoustic waves have two different propagation paths: one path is directly reflected by the surface of the specimen, the other path is travelling along the surface with Rayleigh angle θ_R. Acoustic waves that travel along the first path are a direct reflection echo D, and acoustic waves along the second

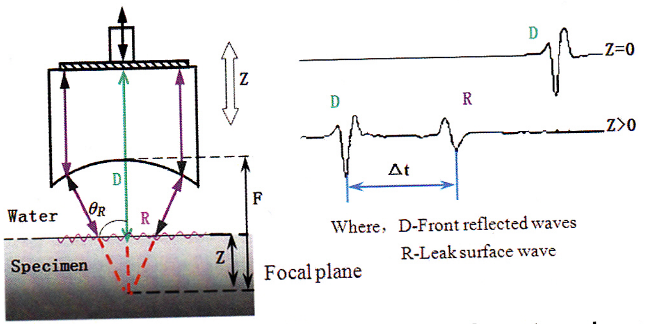


Figure 4. Ray representation of the PVDF line-focus transducer generating the front reflected wave *D* and the leaky surface wave *R*

path, leaking into the specimen and received by the transducer, are a leaky surface wave R.

When the wave velocity of the coupling liquid (typically water) is V_w, the echo signal is measured with a continuous defocus. As mutual interference between leaky surface waves and direct reflected waves, the $V(z)$ curve is a periodic oscillation curve with a period of Δz. By measuring the period of the curve, we can obtain the relationship between the leaky surface wave velocity and Δz at a specific frequency f, as follows[15]:

$$V_R = V_W \left[1 - \left(1 - \frac{V_W}{2 \cdot f \cdot \Delta z} \right)^2 \right]^{-\frac{1}{2}} \quad \text{......................(1)}$$

The oscillation period Δz of the curve is difficult to measure in the time domain; the $V(f, z)$ analysis method[16] uses a two-dimensional Fourier transform. Firstly, we Fourier transform time-domain echo signals into the frequency domain, after that we can get the curve of defocusing distance z *versus* a specific frequency f, which is the $V(f, z)$ curve. Then, Formula (1) and the oscillation period Δz of the curve are used to calculate the surface wave velocity. But the oscillation period is difficult to measure accurately, so the defocusing distance z can be processed by the space-domain Fourier transform, transforming it into wave-number k domain or $1/z$ domain. Then we can obtain the figure of $A(f, k)$ or $A(f, z^{-1})$. The reciprocal of the peak spatial frequency k is the oscillation period at the specific frequency. The leaky surface wave velocity can be calculated accurately by Formula (1).

Studies have shown that test specimens with different mechanical properties possess different oscillating periods of $V(z)$ curves. Using the $V(f, z)$ analysis method, the dispersion curves of Lamb waves for sheets and coated materials can be obtained[17-18], and then the mechanical parameters of specimens can be calculated by fitting the theoretical curve to the experimental curve.

4. Surface wave velocities measurement

In addition, the system can measure wave velocity along different propagation vectors on the test specimen's surface. The angles between the transducer's focus line and the specimen's primary axis can be changed by rotating the support stage (*ie* Rz-axis).

This paper employed the system to measure surface wave velocities of anisotropic materials such as (100) silicon wafer at different angles from 0° to 360°, and to verify the reliability of the system and the accuracy of the measurement results by detecting the symmetry of the silicon crystal axis.

The transducer is a line-focus PVDF transducer with a centre frequency of 9 MHz, a focal distance of 20 mm and an aperture angle of 85°. A Φ76.5 mm × 10 mm (100) silicon wafer sample is placed into the tank on the turntable with the centre axis of the sample coincident with the z-axis. Before making a measurement, the position of the line-focus transducer can be adjusted until its focus line coincides with the specimen's surface diameter, and defining the direction perpendicular to the focusing line as the initial angle (θ = 0°). The measurement of surface wave velocity starts with the initial angle (θ = 0°) and measurements are taken at 2° intervals. Surface waves propagating between the transducer and test specimen are shown in Figure 5.

As the propagation path of the surface wave is the same within each 90° interval, the surface wave velocities need only be measured from 0° to 90°, but the velocities have actually been measured from 0° to 360° in order to test the reliability and consistency of this system.

At each angle, the measurement process of surface wave velocity is as follows. The line-focus PVDF ultrasonic transducer steps down from the focus position and acquires the echo signal at each defocus position. The step is 0.025 mm and the defocus distance is 10 mm; the sum of echo signals is 401 groups. Then, the $V(f, z)$ method is used to process and analyse these echo signals. Finally, the velocity

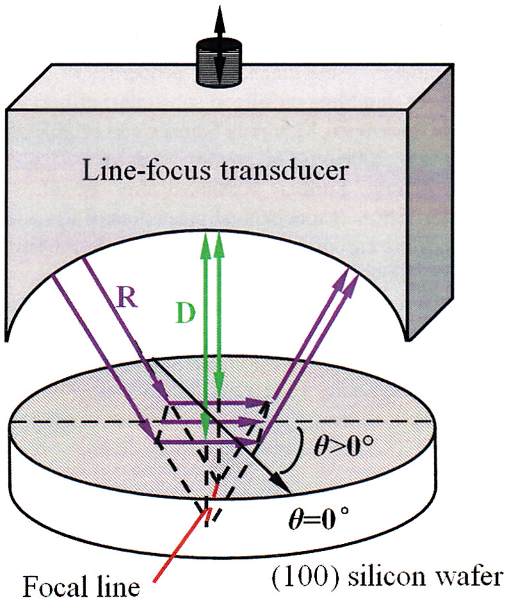
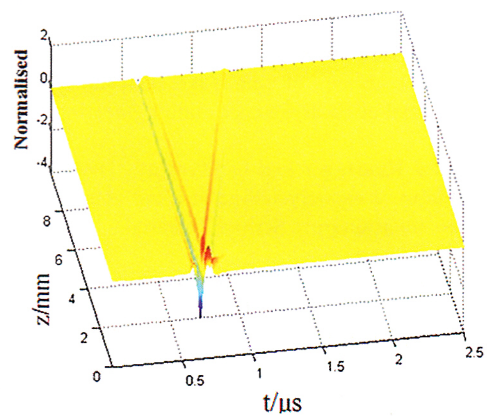
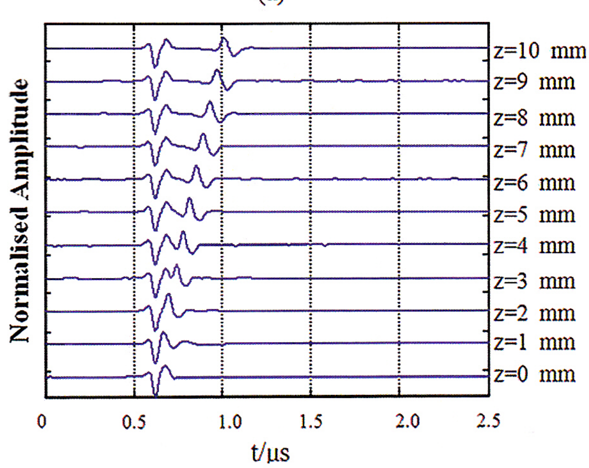


Figure 5. The sketch map of measuring (100) silicon wafer by the PVDF line-focus transducer

of surface waves along each direction is calculated. Figures 6, 7 and 8 are the analysis process of surface wave velocity when θ is 8°. Figure 6(a) shows 401 groups of echo-signal waveforms of the time domain in 3D and Figure 6(b) shows the normalised waveforms for the time domain at defocus distances varying from 0 mm to 10 mm. Figure 7 shows 401 $V(f, z)$ curves transformed by 1D-FFT. Figure 7(a) shows 3D waveforms in the frequency domain and Figure 7(b) shows normalised waveforms in the frequency domain.



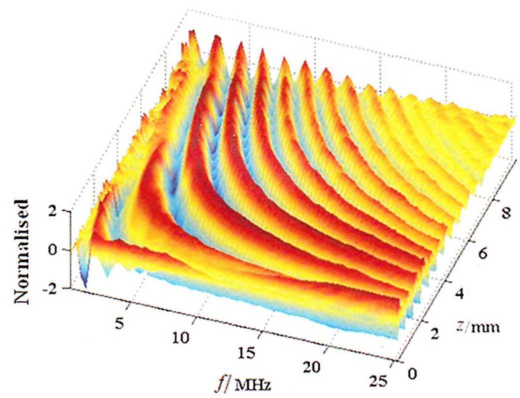
(a)



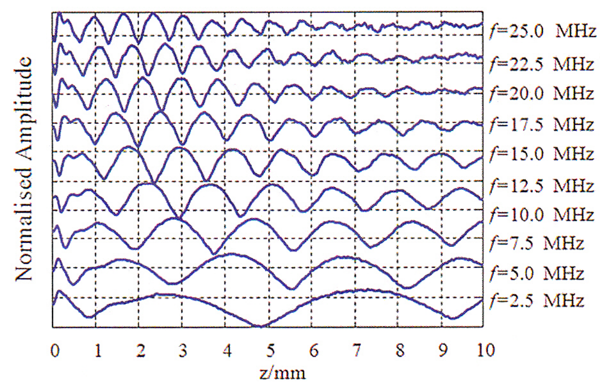
(b)

Figure 6. Time domain waveforms at different defocusing: (a) Measured waveforms of 3D time domain; (b) Normalised waveforms of time

The results of surface wave velocity measurement at $\theta = 8°$ and along different propagation directions from 0° to 90° are shown in Figure 8. Figure 8(a) shows $A(f, z^{-1})$ curves by 2D-FFT transform. Formula (1) shows that the oscillation periods Δz at different frequencies f can be used to calculate surface wave velocities.



(a)



(b)

Figure 7. $V(f, z)$ curves by 1D-FFT transform: (a) 3D frequency domain waveforms; (b) Normalised frequency domain

Finally, tracing out the peak spatial frequency at specific frequencies f in the $A(f, z^{-1})$ curve, the dotted lines are traced peaks of $A(f, z^{-1})$ as shown in Figure 8(a). Coordinate values that correspond to these peaks are f and $1/\Delta z$. The surface wave velocities can be calculated at different frequencies by substituting f, Δz and longitudinal wave velocity C_w into Formula (1). Figure 8(b) shows that surface wave velocities are non-dispersive when obtained at 8°. The average of these velocities at different frequencies is the surface wave velocity at this angle. Figure 8(c) shows surface wave

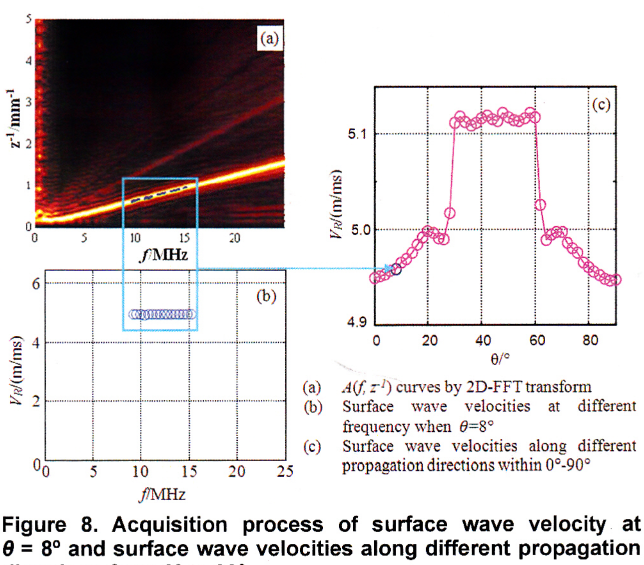


Figure 8. Acquisition process of surface wave velocity at $\theta = 8°$ and surface wave velocities along different propagation directions from 0° to 90°

velocities along different propagation directions from 0° to 90°.

The same method can be used to measure the surface wave velocity along different propagation directions from 0° to 360° at 2° intervals. Figure 9 is the polar chart of surface wave velocities for (100) silicon wafer along different propagation directions from 0° to 360°. The Figure shows that surface wave velocities of (100) silicon wafer cycle every 90°, and that the surface wave velocities are nearly identical in different cycles. In particular, surface wave velocities at two propagation paths whose separation angle is 180° have good repeatability. This shows that the system could measure surface wave velocities of anisotropic materials such as (100) silicon wafer at different angles from 0° to 360°, and that this system has superiority in accuracy, reliability and consistency.

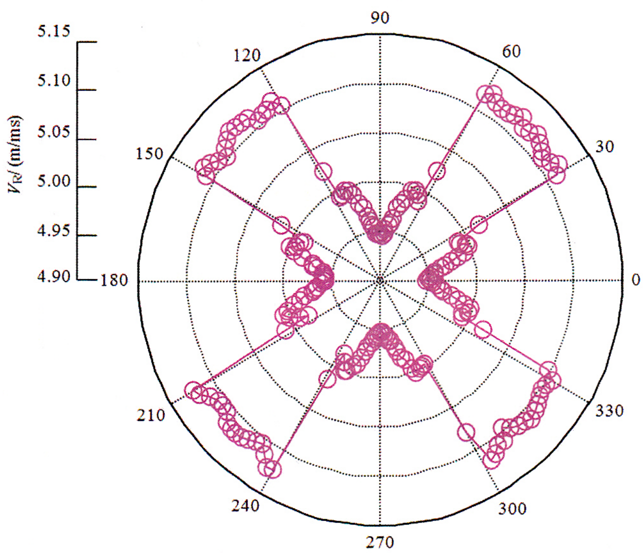


Figure 9. Polar chart of surface wave velocities for (100) silicon wafer along different propagation directions from 0° to 360°

5. Conclusion

The paper presents the details of the components for a high-precision ultrasonic microscopy measurement system, as well as the principles and methods of surface wave velocity measurement using this system. The surface wave velocity is measured along different propagation directions of a (100) silicon wafer surface. The experimental results are accurate and reliable, and the development and study show that the high-precision ultrasonic microscopy measurement system has high movement resolution, positioning accuracy and good reliability. It can therefore meet practical measurement requirements. Surface wave velocity along different propagation directions can be measured by a lensless focus transducer. The system can be used to measure both isotropic and anisotropic materials. Precision ultrasonic test systems and $V(f, z)$ analytical methods may be used to obtain the wave velocity at the different frequencies. It can be used to measure not only the non-dispersive surface wave velocity, but also the dispersion curve of Lamb waves.

This study has laid the foundation for the ultrasonic non-destructive testing of mechanical properties of unconventional materials.

Acknowledgements

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References

1. Yifang Cao, S Allameh and D Nankivil, 'Nanoindentation measurements of the mechanical properties of polycrystalline Au and Ag thin films on silicon substrates: effects of grain size and film thickness', Materials Science and Engineering A, 427, pp 232-240, 2006.
2. Feifei Zhang, Sridhar Krishnaswamy *et al*, 'Ultrasonic characterisation of mechanical properties of Cr- and W-doped diamond-like carbon hard coatings', Thin Solid Films, 503, pp 250-258, 2006.
3. Yung-Chun Lee, 'Measurements of dispersion curves of leaky Lamb waves using a lensless line-focus transducer', Ultrasonics, 39, pp 279-306, 2001.
4. Liu Dongxu, Zhang Taihua and Huan Yong, 'Development of macro-depth-sensing indentation instrumentation', Chinese Journal of Theoretical and Applied Mechanics, 39 (3), pp 350-355, 2007.
5. Xie Huimin, Liu Zhanwei and Zhu Hongwei, 'Study on mechanical behaviour of single-wall carbon nanotubes by using digital speckle correlation method (DSCM)', Optical Technique, 30 (4), pp 449-454, 2004.
6. Song Guorong, He Cunfu and Liu Zenghua, 'Measurement of elastic constants of limited-size piezoelectric ceramic sample by ultrasonic method', Measurement, 42 (8), pp 1214-1219, 2009.
7. Song Guorong, He Cunfu and Wei Xiaoling, 'Development of an ultrasonic system to measure material elastic constants of small sample', Chinese Journal of Scientific Instrument, 27 (9), pp 1012-1015, 2006.
8. Song Guorong, He Cunfu and Huang Yao, 'Design of line-focus PVDF ultrasonic transducer for elastic constant measurement of limited-size samples', Chinese Journal of Scientific Instrument, 29 (11), pp 2298-2303, 2008.
9. Song Guorong, He Cunfu and Huang Yao, 'On the measurement of the elastic constants of small-size samples by ultrasonic method', Journal of Basic Science and Engineering, 15 (2), pp 226-234, 2007.
10. H S Cao, J J Hunsinger and O Elkedim, 'Determination of elastic modulus of nanocrystalline iron and titanium by means of acoustic microscopy', Scripta Materialia, 46, pp 55-60, 2002.
11. R S Gilmmore, K C Tam, J D Young *et al*, 'Acoustic microscopy from 10 to 100 MHz for industrial applications', Acoustic Microscopy for Industry, A320, pp 215-235, 1986.
12. J O Kim and J D Achenbach, 'Acoustic microscopy of the elastic properties of TiN/(VxNb1-x)N superlattices', Physical Review B, 48 (3), pp 1726-1737, 1993.
13. N Guo and P Cawley, 'Lamb wave reflection for the quick non-destructive evaluation of large composite laminates', Materials Evaluation, 52 (3), pp 404-411, 1994.
14. A Briggs, Acoustic Microscopy, Oxford University Press, New York, 1992.
15. J Kushibiki and N Chubachi, 'Material characterisation by line-focus-beam acoustic microscope', IEEE Transactions on Sonics and Ultrasonics, 32 (2), pp 189-212, 1985.
16. D Alleyne and P Cawley, 'A two-dimensional Fourier transform method for the measurement of propagating multi-mode signals', Journal of the Acoustical Society of America, 89 (3), pp 1159-1168, 1991.
17. Yung-Chun Lee and Sheng-Wen Cheng, 'Measuring Lamb wave dispersion curves of a bi-layered plate and its application on material characterisation of coating', IEEE Transactions on UFFC, 48 (3), pp 830-837, 2001.
18. Feifei Zhang, Sridhar Krishnaswamy *et al*, 'Bulk wave and guided wave photoacoustic evaluation of the mechanical properties of aluminium/silicon nitride double-layer thin films', Ultrasonics, 45, pp 66-76, 2006.