# DEVELOPMENTS IN LOW COST OPTICAL DETECTION AND SIGNAL PROCESSING FOR LASER ULTRSONICS

L.-K. Shark[1], P. L. Salter[2], J. P. Smith[3] and C. Yu[1]
[1] ADSIP Research Center, University of Central Lancashire, Preston, UK
[2] Advanced Technology Centre, BAE Systems, Bristol, UK
[3] Materials Engineering and Test, BAE Systems, Preston, UK

**Abstract:** Laser ultrasonics is an emerging non-destructive testing technique. It offers several advantages over conventional water-jet ultrasound inspection, including improved spatial resolution, scanning speed and ability to inspect complex shaped components. Presented in the first part of the paper are the developments of a low cost optical detector for laser ultrasonics based on the photo-EMF (electromotive force) principles with a relatively inexpensive CW laser, and the detector performance tested using aluminium and carbon fibre composite panels with ultrasound generated by a conventional piezoelectric (PZT) transducer. Whilst the photo-EMF detector is shown to have the advantage of compactness and simple optical design, it is seen to suffer from low sensitivity. The signals obtained are overwhelmed by noise, particularly those obtained from low reflectivity composite materials, making it difficult to take proper measurement of ultrasonic attenuation and time-of-flight. A simple and effective way to improve signal quality will be to reduce noise by averaging of multiple laser ultrasonic waveforms, but this will significantly reduce scanning speed and potentially cause surface damage. Hence, this leads to the developments in signal processing presented in the second part of the paper. By employing the continuous wavelet transform and kurtosis information to enhance echo features and to suppress the influence of noise respectively in the high-order time-scale domain, an automatic method is presented for the estimation of ultrasonic attenuation and time-of-flight from a single shot laser ultrasonic waveform, and the estimation is shown to be in agreement with those measured from the averaged laser ultrasonic waveforms. The work is not only encouraging in demonstrating improved utilisation of low cost optical detectors, but also the techniques can be applied to any noisy ultrasound signals such as those received from thick and/or multi-layered components.

**Introduction:** Laser ultrasonics [1-2] offers significant advantages over conventional "water-jet" ultrasound inspection, e.g. spatial resolution, sensitivity and, most notably, speed. This latter characteristic becomes especially dominant in the case of complex geometry structures where ten-fold (or more) increases in testing throughput have been reported. The increasing use of such structures for modern aircrafts has seen an increasing adoption of laser ultrasonics by the aerospace industry. Laser ultrasonics offers the potential to save on the costs of inspection by reducing inspection times and avoiding the necessity to construct complex scanning equipment for complex geometry components. The advantages of laser ultrasonics over conventional water jet ultrasonic scanning include:

a) it is non-contacting and does not require complex transducer mounting jigs.
b) it can access complex geometrical shapes, due to its capability to operate over a wide range of detection angles.
c) there is no requirement for a coupling fluid to improve efficiency.
d) it offers high resolution compared to contact transducers.
e) it can provide a broadband flat frequency response and hence improve depth resolution, which is difficult to achieve for contact transducers, especially at high frequencies.
f) large components can be scanned rapidly.

A laser ultrasound system fundamentally consists of two distinct aspects, namely, laser generation of ultrasound in the test material, and laser detection of ultrasound. In laser ultrasonics the transducers that are used to generate and detect the ultrasound in conventional water-jet C-scan inspection are replaced by a generation laser and a detection laser. Whilst, ideally, these two roles would be achieved by one and the same laser, in practice this is not possible, since the requirements for generation are totally distinct from those for laser detection. However, the properties of one will impact on the performance requirements of the other e.g: the sensitivity of the detection system will help to determine the energy requirements of the generation laser.

In general, sensitive optical detection systems are expensive and are either optically complex (e.g confocal Fabry-Perot systems requiring active stabilisation) and often require the use of complex expensive single longitudinal mode long pulse laser systems. The paper presents the attempt made to develop a compact and low cost optical detection system for laser ultrasonics, based on the photo-EMF (electromotive force) principles with a relatively inexpensive continuous wave (CW) laser, and a novel signal processing method employing the kurtosis information in the wavelet domain to enhance ultrasonic echoes [3-4].

**Photo-EMF Detection:** The principles of photo-EMF detection was first described by Sokolev and Stepanov [5-6]. It is a solid-state device, similar to a conventional semiconductor optical detector, which develops and stores an internal electric field that reproduces the spatial intensity pattern of the incident illumination. When the intensity pattern moves or vibrates laterally, the stored space-charge field drives a time-varying current through the electrical contacts on either side of the detector. This current can then be amplified in the normal way to produce the output signal.

Physically, the detector consists of a photo-conductive crystal (GaAs:Cr crystal in the Lasson detector) [7]. In its application to laser ultrasound detection, the detector is arranged as part of a normal homodyne reference beam interferometer [8-9]. The signal and reference beams are combined at a small angle (typically 1.5 degrees) within the interferometer and generate an intensity fringe pattern on the surface of the crystal. Photocarriers are produced in the high intensity regions of the fringe pattern and these diffuse away from the high intensity regions, become trapped, and form a stationary charge pattern which generates a stationary space charge field. In the absence of a change in the light intensity pattern no net current flows through the external circuit. If the movement or modulation of the light intensity is slow (dependent on the carrier response time of the material) then the space charge distribution will track the fringe pattern movement and again no resulting current will be generated. However, when the intensity pattern is modulated by fast displacements (such as high frequency ultrasound), the fringes will move relative to the stationary space charge distribution and a current will be generated.

The detector thus has the ability to sense high frequency ultrasound displacements while compensating or adapting for low frequency disturbances, such as those caused by environmental vibrations. This compensation frequency range is typically up to 100kHz, which is adequate for most rigid body/environmental disturbances, whereas the ultrasonic frequency response of this type of detector is inversely proportional to the carrier recombination time and can be as high as 30MHz.

The bandwidth is limited by the electronics and in the present system the detector electronics have a bandwidth of 10MHz. Detector modules offering higher electronic bandwidths (to 25MHz) are available.

The principal advantage of this type of detector is that it is compact and combines optical compensation and detection as well as electronic post-processing in one semiconductor element. Other advantages are:

- It collects light from several speckles and is, therefore, suited to rough surfaces.
- Although it is a reference beam interferometer it does not require path length stabilization.
- It generates an analogue signal proportional to displacement above a cut-off frequency (typically 100kHz). Below this the signal is proportional to surface velocity.
- It is unaffected by low frequency acoustic noise or turbulence in the beam path – it is a compensated detector.

The optical arrangement of the detector system is shown in figure 1. The input laser beam enters the interferometer, passing through a half-wave plate (HWP) and polarising beam splitter (PBS1) which splits the source into orthogonal, linearly polarized, reference and probe beams. Rotation of the half-wave plate alters the plane of polarization of the input beam and thus allows the relative intensities of the reference and probe beams to be adjusted.

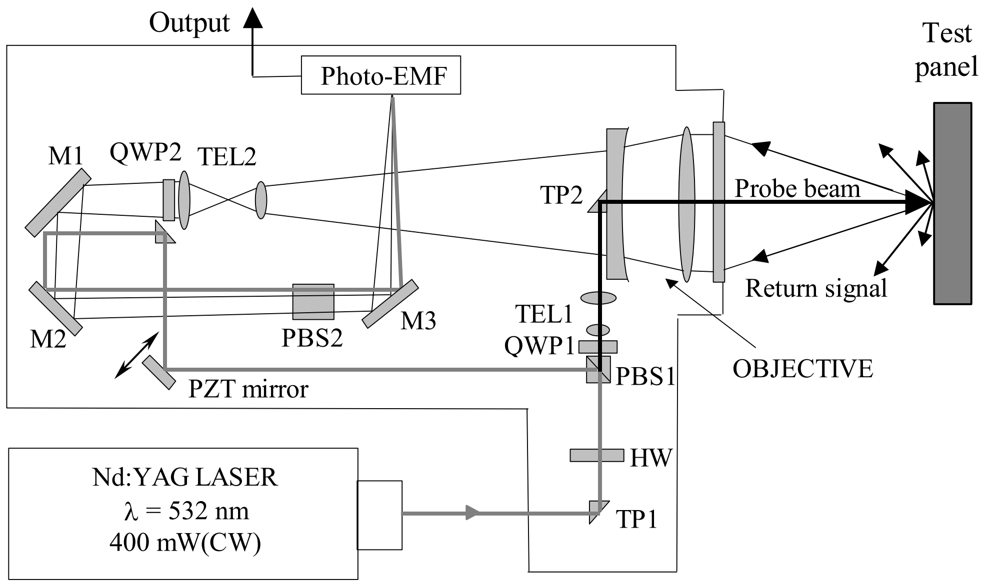



Figure 1 Schematic layout of Lasson photo-EMF receiver

To overcome any polarization sensitivity on the target the probe beam is circularly polarized via a quarter-wave plate (QWP1) (This also ensures that the return beam is effectively blocked from re-entering the laser cavity). The beam is then expanded, using a small telescope (TEL1), and is directed by a turning prism (TP2) through the centre of the collection lens to the sample surface. Light scattered from the sample surface is collected by the large diameter collection lens and directed through a small collimating telescope, a quarter-wave plate (to restore vertical polarisation as for the reference beam) and turning mirrors onto the photo-emf detector chip. The reference beam is inclined at a small angle (typically 1.5 degrees) with respect to the object beam to create a fringe pattern on the detector. A PZT mounted mirror which operates around 1MHz can be used to modulate the reference beam to simulate an ultrasonic signal for alignment of the interferometer.

Alignment of the system essentially involves ensuring that the input laser beam lies on the optic axis of the system. At the outset this proved to be quite a sensitive operation and so a common baseplate was designed which allowed fine adjustment of the laser position.

A metal target, on an adjustable mount, is used to obtain a good signal beam for alignment purposes. A simulated ultrasonic signal is obtained by modulation of the reference beam using a PZT driven mirror (this is done via a signal generator providing approximately 0.8-1.2 MHz signal at $10V_{p-p}$ to drive the mirror through several microns). This results in a sinusoidal signal on the oscilloscope, which is optimised by adjusting the orientation and distance of the target. A 2.5MHz low pass filter provides a smoother signal while adjustment is carried out. Further optimization of the signal is obtained by adjustment of the half waveplate to maximise the intereference between object and reference beams.

The receiver can be used with different extension lenses on the output to provide nominal target ranges of 200mm, 500mm and 1000mm. The amplitude of the sine wave depends critically on the distance of the focus point and the reflectivity of the target. The sensitivity of the receiver to the target distance was measured experimentally by monitoring the half-amplitude values of the signal. The results indicate that for the 200mms, 500mms and 1000mm focussing distances the half amplitude ranges are ±1.25mm, ±5mms and ±25mms respectively.

The alignment is also sensitive to orientation of the test panel. At an object distance of 200mms the half amplitude value occurs for deviations of ±5 degrees to the optic axis. At 1000mm this tolerance is reduced to ±1.7 degrees.

**Detection of Ultrasound :** Figure 2 shows the experimetal arrangement for the photo-EMF reveiver to detect ultrasound generated by a conventional piezoelectric (PZT) transducer. The laser employed is an ADLAS (coherent) frequency doubled, diode pumped, Nd:YAG laser having wavelength λ = 532nm and providing a maximum CW power of 400mW. To avoid the effect of heating and surface damage, the exposure time of the laser on the component surface is limited by using a programmable shutter controlled by a pulse generator. The PZT transducer is driven by high voltage and high frequency square wave pulses at a 2kHz repetition rate from the Staveley Instruments SONIC-136 ultrasound pulser. The photo-EMF receiver's output signal is displayed on the oscilloscope's screen, and downloaded to a PC from the GPIB interface of the oscilloscope to the serial port of the PC via a GPIB to RS232 converter (Tastronic). By utilizing the features of the "Smart Trigger" facility of the LeCroy oscilloscope, the signal is triggered from the ultrasonic pulser (SONIC 136) during the shutter open period.

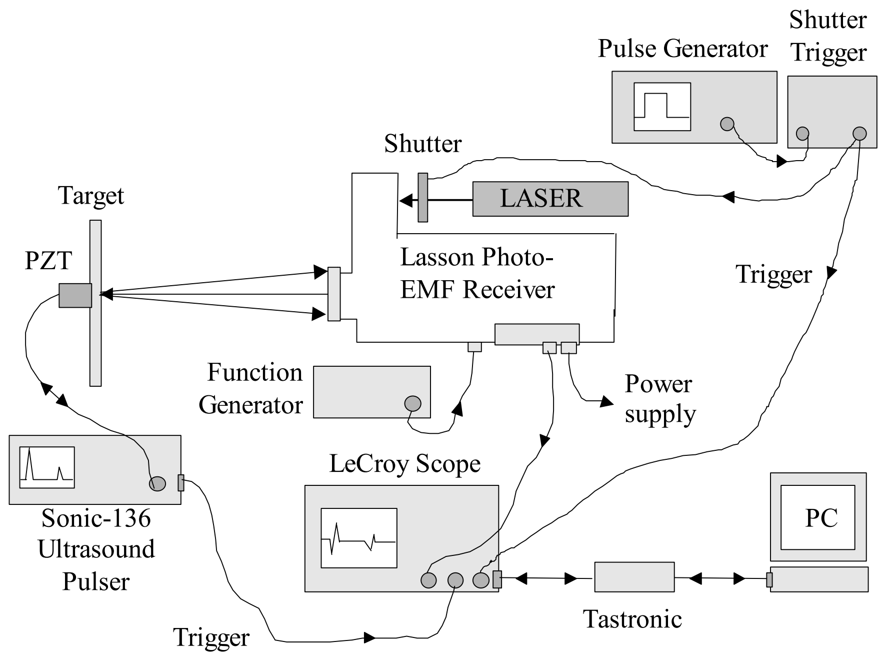
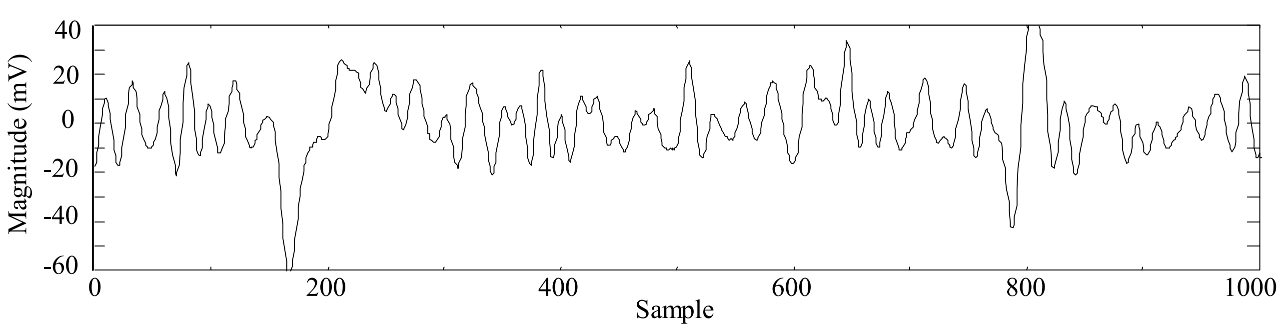



Figure 2 Experimental arrangement

In the work, two different PZT transducers (5MHz and 10MHz) were used for ultrasonic exitation, and two different type of test panels (aluminium plates and carbon fibre panels manufactured from woven fibre) with a thickness of 9mm were used for testing. Figure 3 shows three typical laser ultrasonic signals detected by the photo-EMF receiver, where Figure 3(a) is obtained from an aluminium plate in response to 10MHz ultrasonic excitation, and Figures 3(b) and 3(c) are obtained from a carbon-fibre panel with 5MHz and 10MHz ultrasonic excitations respectively. From Figure 3, whilst reasonably good signal levels can be achieved with aluminium materials, the signals obtained with composite materials are overwhelmed by noise. Whilst the first ultrasonic echo can be identified in general, the second ultrasonic echo is embedded in rapid high-amplitude fluctuation. Furthermore, the noise level is seen to increase when the excitation frequency increases.



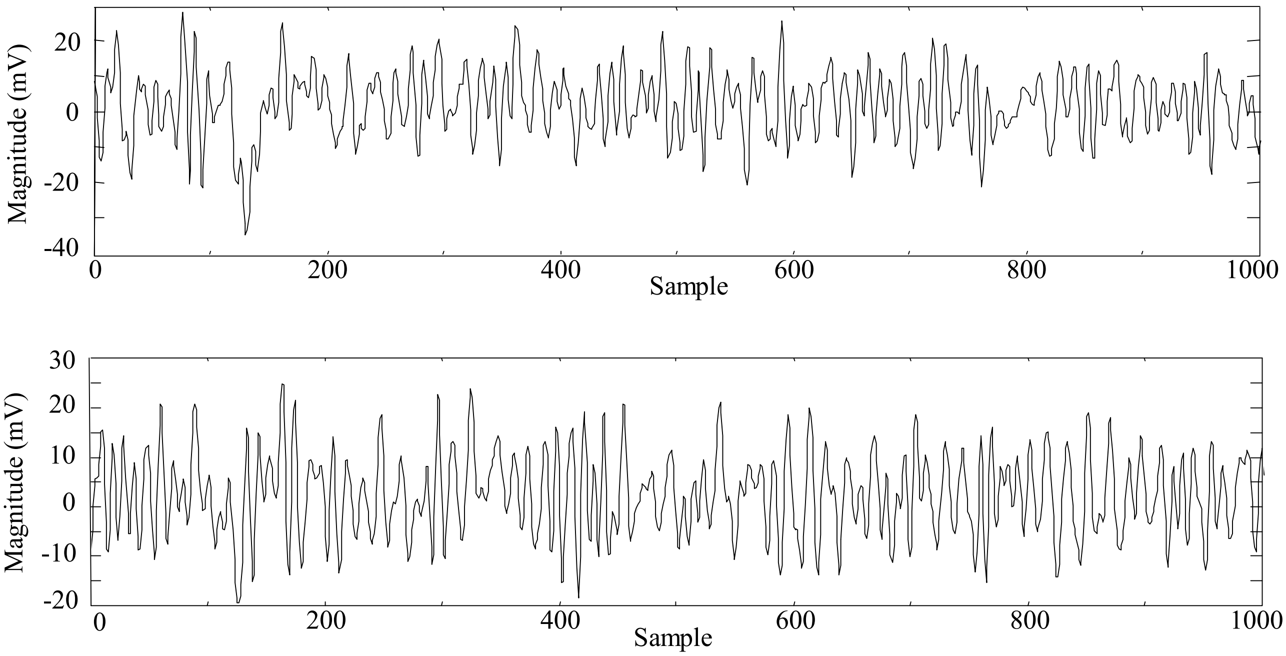
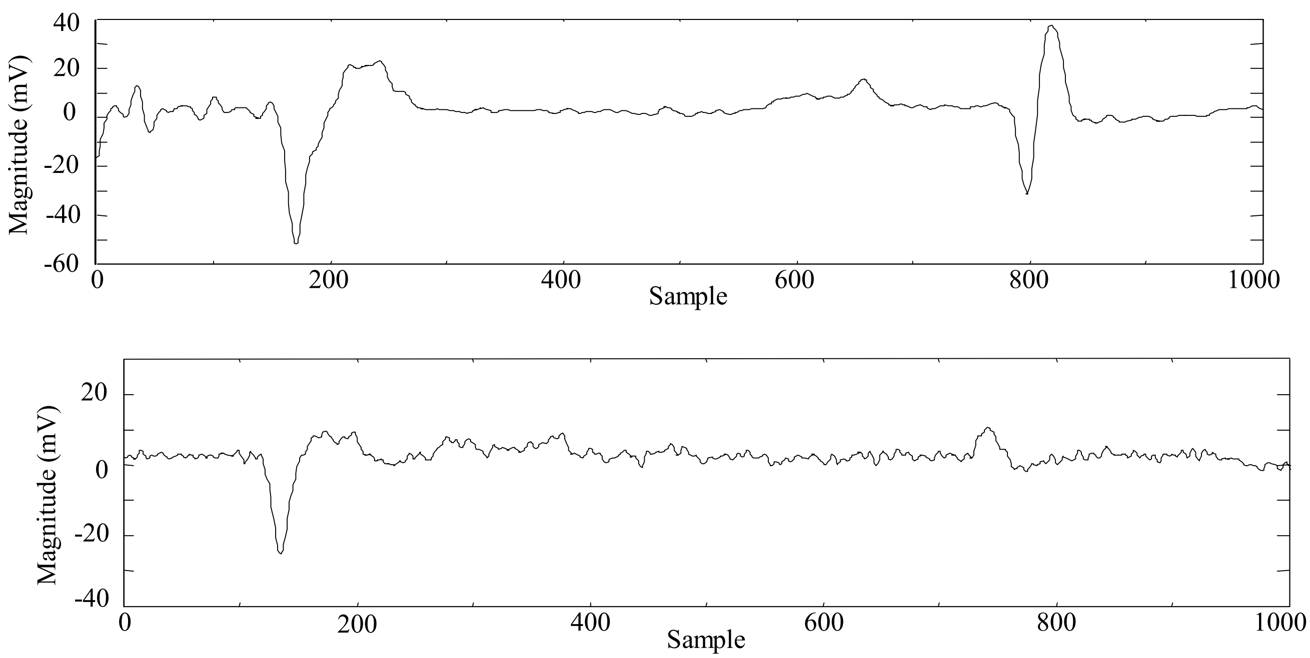



Figure 3 (a) Aluminimum with 10 MHz PZT, (b) Composite with 5 MHz PZT,
and (c) Composite with 10 MHZ PZT

Assuming noise to be random, an effective and simple way to enhance ultrasonic echoes is to arverage multiple waveforms. By using the waveform average function of the oscilloscope and the same set-up to obtain the single waveforms shown in Figure 3, Figure 4 shows the corresponding three waveforms with each obtained by avearging of 128 waveforms, where both the first and second ultrasonic echoes are seen to be clearly visible. Whilst signal averaging produces desired outputs, it slows down the scanning speed and has the potential of damaging component surface due to the increased exposure time. This leads to the development of the signal processing method presented in the next section.



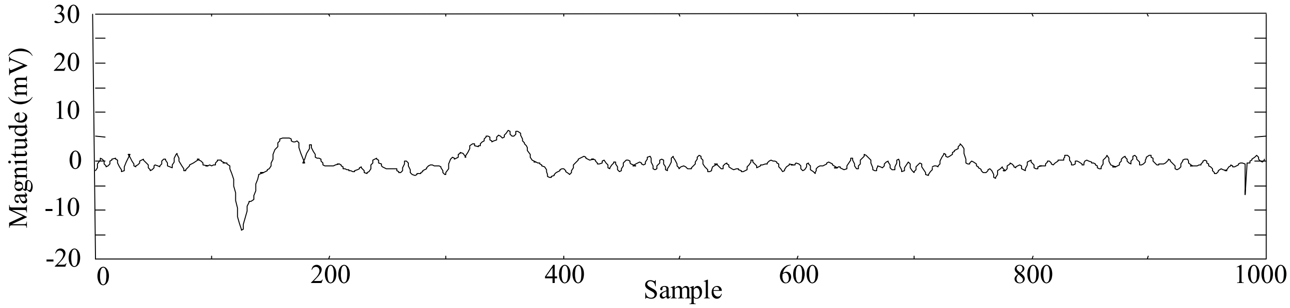



Figure 4 Averaged waveforms for (a) Aluminimum with 10 MHz PZT, (b) Composite with 5 MHz PZT, and (c) Composite with 10 MHZ PZT

**Signal Processing for Automatic Parameter Estimation :** Ultrasonic attenuation and time-of-flight are two parameters commonly used to characterise the material under test, and are estimated based on the ratio of and the distance between the maximum amplitude values of the first and second echoes in the waveform. Although a number of automatic estimation methods are available [10-11], they can not be directly applied to laser ultrasonic signals because of the high noise level. If the averaged waveforms are treated as the true signal desired, then the signal-to-noise ratio (SNR) for the single waveforms are estimated to be 0.57dB for the aluminium plate, and –7.5dB and –11.4dB for the composite panels with 5MHz and 10 MHz ultrasonic excitations respectively. For the latter cases with the noise level exceeding significantly the signal level, it is not possible to estimate ultrasonic parameters directly in the time domain.

Instead of processing in the time domain, the proposed signal processing method uses the continuous wavelet transform (CWT) to enhance the echo features of the laser ultrasonic signal in the time-scale domain. Since the CWT can be interpreted as correlation of the signal and the appropriately scaled and translated wavelets. When the scale factor is small, the wavelet is compressed and the corresponding wavelet coefficients contain mainly the high frequency components of the signal revealing its local fluctuations. When the scale factor increases, the wavelet is stretched and the corresponding wavelet coefficients contain mainly the low frequency components of the signal revealing its general trends. To optimize the correlation peaks in the time-scale domain, the CWT is performed using a special wavelet based on the Mexican-hat function and designed to match the first echo in the averaged wavelet.

According to high-order spectral analysis, high-order cumulants (except mean and variance) provide a high signal-to-noise representation, whereby the influence of white Gaussian noise is completely removed, and other kinds of noise are greatly suppressed. If the noise in laser ultrasonic signals is assumed to be Gaussian, then the CWT of the Gaussian noise is also Gaussian, and high-order cumulants of the CWT should suppress further the influence of noise in the time-scale domain thereby enhancing ultrasonic echoes. Since the $3^{rd}$ order cumulant suppresses not only Gaussian processes, but also all symmetrically distributed processes such as almost symmetrical ultrasonic echoes, it is not adopted and the $4^{th}$ order cumulant, also called kurtosis, is used instead. In the implementation, the kurtosis is computed based on a window sliding across each scale of the CWT and periodic extension is used for boundary positions. Using Figure 3(b) as an example, Figure 5 shows the corresponding CWT and its kurtosis. In the CWT shown in Figure 5(a), whilst the highest peak caused by the first echo is clearly seen, the peak caused by the second echo is less obvious as it has a magnitude value comparable with those of many other small peaks caused by noise. Although it is possible to detect the peak caused by the second echo directly in the time-scale domain as it is reasonably visible, the probability of false detection could be high due to the surrounding peaks caused by noise. In the kurtosis of the CWT shown in Figure 5(b), with the majority of the small peaks caused by noise suppressed, the peak caused by the second echo is seen to stand out, and the probability of false detection will be low.

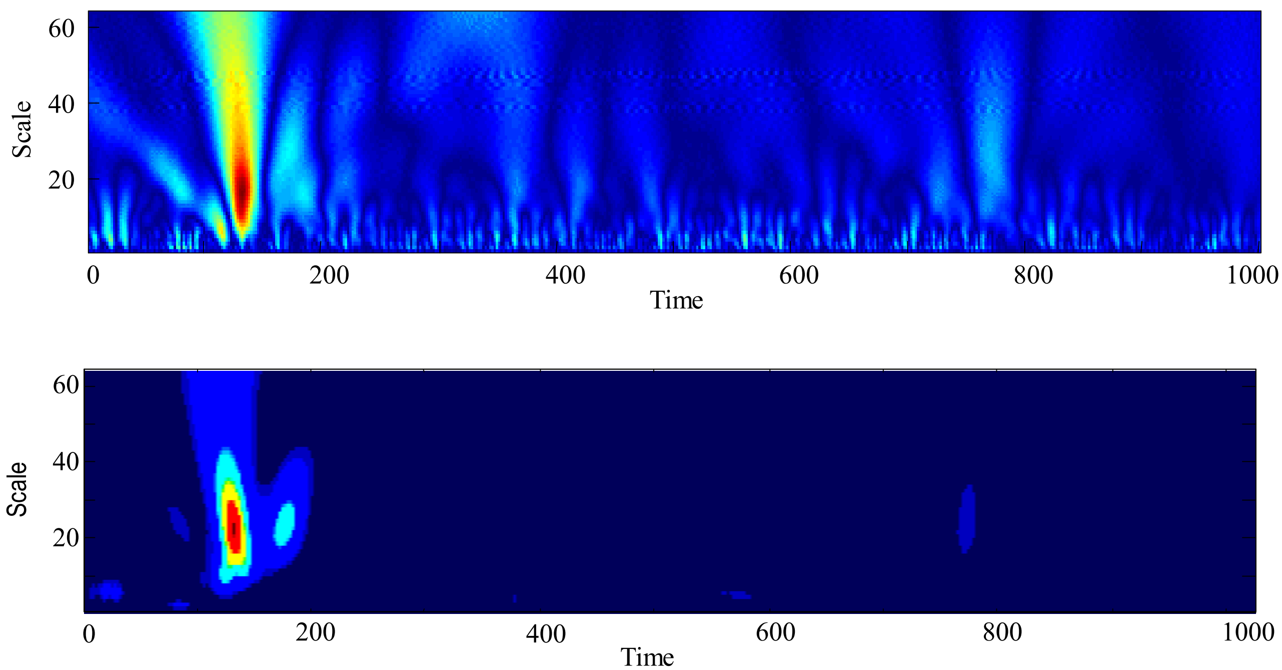



Figure 5 (a) CWT of the signal shown in Figure 3(b), and (b) kurtosis of CWT

With the ultrasonic echoes shown as distinctive peaks in the high-order time-scale domain, the next step is to identify automatically their positions and magnitudes to yield ultrasonic time-of-flight and attenuation. Whilst the first ultrasonic echo is identified by finding the maximum magnitude value, $P_0$, and its position in the high-order time-scale domain, the second ultrasonic echo is identified by searching the next maximum magnitude value, $P_1$, with the search start from a predefined offset from the position of $P_0$ in the time direction and confined in the neighbourhood of the scale of $P_0$. With the two peaks found, the ultrasonic time-of-flight is given by their separation distance, and the ultrasonic attenuation is given by $\alpha = \sqrt[4]{P_1 / P_0}$ .

For the three laser ultrasonic signals shown in Figure 3, the ultrasonic time-of-flight and attenuation are estimated manually from the corresponding averaged waveforms, and compared with those estiamted using the proposed signal processing method described above. Table 1 lists the results obtained. The relative closeness between the two sets of values demonstrates the validity of the proposed approach.

Table 1

| | Time-of-Flight | | Attenuation | |
|---|---|---|---|---|
| Test Panel/PZT | Averaged waveform | Proposed Method | Averaged Waveform | Proposed Method |
| Alunimium/10MHz | 6.38 μs | 6.40 μs | 0.6364 | 0.6170 |
| Composite/5MHz | 5.95 μs | 5.95 μs | 0.2914 | 0.3214 |
| Composite/10MHz | 5.98 μs | 6.35 μs | 0.2929 | 0.3925 |

**Conclusions :** Based on the photo-emf receiver and signal processing methods, the paper presents the preliminary development of a low cost optical detection system for laser ultrasonics. Although the photo-emf receiver is seen to produce signals with high level of noise, the proposed signal processing method is shown to be able to determine automatically the ultrasonic time-of-flight and atteuation by correct extraction of ultrasonic echoes in the high-order time-scale domain. The work is not only encouraging in demonstrating the possibility of a compact, rugged, simple and light weight laser ultrasonic system, but also the developed signal processing techniques can be applied to any noisy ultrasound signals such as those received from thick and/or multi-layered components.

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