Int. Journ. of Peening Science and Technology, Vol. 1, pp. 183–199
Reprints available directly from the publisher
Photocopying permitted by license only.

Characterization of Laser Ultrasonic in Ablation Regime Using Filter and Hilbert Transform

D. MANGAIYARKARASI, VINUTHASHRI, T. ZHENKUI,
K. O. Y. KENG, C. LONG, S. H. WEI, S. YALI,
C. LIANWEI AND M. HONG*

National University of Singapore, Engineering Faculty, Electrical and Computer Engineering Department, Optical Science and Engineering Centre, E6-03-03, 5 Engineering Drive 1, Singapore 117608

Laser generated ultrasound in ablation regime provides a large enhancement of longitudinal mode signal which is useful to investigate defects and monitor thickness of offshore structures in real time. However, the simultaneous generation of bulk and surface acoustic waves (SAW) create complexities in the detection of appropriate type of ultrasonic wave. This is due to strong surface waves, which propagate along the surface interface regions interfering with the reflected longitudinal mode signals from the defects as well as from the rear substrate surface. Thus, the signal is mostly overlapped or hidden in the tail of the surface waves detected causing the determination of the arrival time of the ultrasound a challenging one. This paper utilizes the property of different frequency distributions of the bulk and surface waves and applies filtering functions together with Hilbert transform (HT), which gives instantaneous frequency and amplitude in order to separate and extract the detailed features of the ultrasound signal. A single, distinct, unipolar waveform (positive peak) obtained with bandpass filter followed by HT combination enhances the signal amplitude which is essential for B and C scans in the laser ultrasonics where the threshold voltages are set by the positive peak voltages.

Keywords: Laser ultrasonics, ablation, plasma physics, pulsed laser, signal processing, hilbert transform, surface acoustics waves

Corresponding author's e-mail: elehmh@nus.edu.sg

1 INTRODUCTION

1.1 Laser Ultrasonics

Non-destructive testing and evaluation (NDT&E) together with structural health monitoring (SHM) are two most common approaches used in structural investigations of materials with the advantage of real-time detection to forecast the remaining life cycles of structures and to reduce maintenance costs and time [1]. Ultrasound detection has been implemented as a NDE tool in various areas, including thickness measurements and defect detection for many decades [2]. The problems using conventional piezoelectric transducers are the need to use a coupling medium, limited bandwidth, limitation of operational use at elevated temperatures and the requirement of proper orientations of the phase sensitive piezoelectric transducer for contoured structures. These limitations can be overcome by laser ultrasonics which has the flexibility in generating ultrasound over a wide range of frequencies, transmitting and receiving ultrasound without a coupling medium, the ability to operate in harsh environmental conditions and the detection of specimens with complex geometry [3-7]. Furthermore, the laser source can be focused to the microns scale, at a much higher spatial resolution than the conventional ultrasonic beam source (size at mm scale). Meanwhile, the laser beam can raster over the sample surfaces at a high speed (dozens of mm per second) to increase the NDT throughput. Laser ultrasonics detection is reliable in real industrial situations and presently used for major industrial applications such as wafer inspection, inspection of composite components in aircrafts and wall thickness measurement of seamless steel tubes [8-9].

1.2 Generation of ultrasound with a pulsed laser

When the test sample is irradiated with a short laser pulse (ns or ps) at high energy (mJ), light energy is absorbed strongly by the electrons of the material and transferred to the lattice. Depending on the energy density, it either leads to only a temperature rise (creating thermal waves in the thermoselastic regime) or melting, vaporization and then plasma generation in the ablation regime (producing shock waves) [10, 11]. At a laser density of $< 10^7$ W/cm^2, the thermoelastic mechanism occurs on the metal surfaces. The absorbed laser energy produces thermal expansion and contraction resulting in the production of elastic waves. For the emission of ultrasound along normal to the surface, the penetration of laser beam should be deeper, and the diameter of the beam should be comparable to the wavelength of the ultrasound. However, when the power density increases above 10^7 W/cm^2, in addition to a thermoelastic expansion, the sample surface would melt and material is then ablated to create a pit of a few microns deep. The ejected material and the surrounding air are ionised by various physical process, producing plasma plume and the resulting momentum by the recoiling effect of the outward ejected materials in addition to the plasma pressure produces a point force normal to the surface, which then enhances the amplitude of the ultrasound. In addition to these regimes, there is also a constrained surface source regime that occurs at all power densities in the absence of stress free boundary conditions in the transparent coating that produces normal forces and subsequently enhances the amplitude of the bulk waves even with low power densities. Among these ultrasound generation mechanisms, the ablation/plasma regime provides a large enhancement of longitudinal (compression) and surface waves amplitude to many folds which is essential for some critical applications, such as online monitoring of thickness of seamless steel tubes and for weld quality monitoring at elevated temperatures [12]. Strong attenuation of ultrasound energy occurs in metals at high temperature which is mainly because of the strong background absorption which increases exponentially with temperature and the scattering by the growth of the grain size from a few 10s of microns to 100s of micron with the temperature increase from 1000° C to 1250° C [6].

A laser source of near IR regions of the laser wavelength is used for metals. The frequency or wavelength of the longitudinal ultrasound depends on the pulse duration of laser which is a limiting factor and it controls the amount of information that can be detected. Usually, thinner samples are measured using high frequency ultrasound and thicker samples with low frequency due to the attenuation of ultrasound in high frequency range. For NDT high resolution measurements in microelectronic structures, the theoretical minimum measurable thickness is one wavelength. So, the thinnest sample or micro void size of μm is measured using short laser pulse (ps) to get high frequency(1GHz) ultrasound signal and hence the shorter wavelengths that are comparable to the sizes. Similarly, moderate duration of the laser pulse (100s of ns) or conventional PZT is used to produce low frequency ultrasound to measure the thicker samples since the attenuation is minimum for low frequency ultrasound [6].

1.3 Detection of ultrasound with a continuous wave laser through optical interferometry

The reflected ultrasound signals from the back surfaces as well as from the defects create a small transient surface displacement (~ 10 nm). These surface displacements can be detected with an interferometer in terms of intensity variations and the detected photocurrents are displayed as voltage output signals with time on an oscilloscope or digitizing electrical processor. As the Fabry -Perot interferometer is less sensitive for low frequencies, there is a need however to measure the surface displacement with rough surfaces, therefore two wave mixing PR interferometers have the best capability to detect broadband signals, were used to overcome these drawbacks. Two wave mixing is a dynamic holographic process where two coherent optical beams (reference beam and signal beam) interfere within a photorefractive crystal (PRC) and the beam emitted from the PR crystals consists of a portion of the transmitted signal beam and also a part of the reference beam, which is diffracted in the direction of the signal beam. The diffracted reference beam appears to be wave-front matched as it is a holographic replication of the signal beam. These effects can be used to compensate for the distorted wave fronts reflected or scattered from the rough sample surface [13-15]. Furthermore it can also compensate for environmental noise if the grating response time is fast enough to adapt to the low frequency noise by changing the refractive index grating according to the change in the interference pattern with the homodyne interferometer, However, for the mid-frequency noise which arises from the motion of the probed object will change the speckle pattern (phase) of the scattered light or change the frequency by Doppler effect. To compensate for the Doppler shift, heterodyne interferometers can be used where frequency of the one of the beam is shifted to produce vibration free signal at the output [15-16].

1.4 Objective and motivation of the present study

Laser ultrasonics is less sensitive in the detection of tiny surface displacement (pm or few nm), a higher amplitude signal in the ablation regime increases the signal to noise ratio by compensating for the long path length in thick offshore structures. With pulsed laser incidence on the test piece, all three regimes produce longitudinal, shear and Rayleigh (SAW) waves at the same time [10, 12]. Compared to thermoelastic regime, where the amplitude of all the modes increases linearly with the power density, a greater extent of enhancement is observed for longitudinal and SAW waves in the ablation regime than shear waves [10]. The Rayleigh wave penetration depth is dependent on the frequency of the ultrasound, thus if the wavelength is comparable to its thickness, it propagates between the two boundaries of the sample as a Lamb wave [17] or otherwise it remains on the surface as surface skimming waves [18-20]. These surface waves are used to detect the microcracks on the surface and to determine the thickness of thin films with high precision [19-20]. Using longitudinal mode which propagates into the bulk of the material, higher amplitude laser generated ultrasound signal with multiple echoes are observed in the transmission mode to measure the thickness of metals using our system. Furthermore, to measure the remaining thickness of complex structures like corroded oil tubes and pipes, and to detect defects from the internal and surface structures, etc reflection mode signal with pulse echo technique provides a straight forward and less complicated method [21-22]. The simultaneous generation of longitudinal and SAW waves make the detection of ultrasound a challenging one in the ablation regime where the interferometry or the EMAT transducers are sensitive to all modes of the laser generated acoustic waves [12, 23] and hence the reflected longitudinal mode signal from the defect can be masked by other modes, especially by higher amplitude surface skimming waves. In this paper, by utilizing the recent advances in digital signal processing technique such as the Hilbert transform with other filtering functions, it provides better signal acquisition method and is able to extract detailed features from the defect signal.

2 EXPERIMENTAL PROCEDURES

2.1 Laser ultrasonic system and measurement methods

The experimental arrangement of the integrated laser ultrasonic system which can measure thickness and detect both surface and internal cracks of various metals used in this study is shown in Figure 1. This system consists of a generation laser, optical interferometry detection system and Labview controller for signal analyses. A Nd:YAG laser operating at a wavelength of 1064 nm and a peak energy of 50 mJ/pulse is focused down to 500 microns and then irradiated on the steel surface for ultrasound generation with high spatial resolution. The pulse duration is 8 ns with a repetition rate of 20 Hz. Then the generated ultrasound propagates from the sample front surface to the rear-side surface and the subsequent surface displacement of the transmitted or reflected ultrasound signal is detected by the two-wave-mixing interferometry, where the transmitted signal and diffracted reference are made to interfere in a photodetector to perform phase demodulation using a 532 nm CW laser. Since the surface displacement caused by the ultrasound is very small, high powered CW laser of 213mW is used for detection (see set-up in Figure 1).

With the optimum pulse duration of 8ns, the ultrasound produced has a centre frequency of 23 MHz and the theoretically calculated minimum measurable defect size or thickness value for steel is 0.26 mm (λ) to obtain good sensitivity. Minimum measurable defect sizes depend on the velocity of sound in the material, which also changes significantly with temperature and reduces the measurement accuracy. In general, the thickness and the defect of the material can be measured using one of the ultrasonic non-destructive testing technique, such as pulse echo [8], resonance [24], or Lamb wave [17]. Though the pulse echo method is a simple technique to implement for real life applications, thinner samples (less than 1mm) are difficult to be measured accurately. It is because the time interval between the incident and echo pulse is very short and overlapping may occur between two successive pulses for metals whose acoustic velocities are high. For precise and high time resolution measurements of thinner samples, the short time interval between the two successive pulses can be recorded using higher frequency ultrasound pulse that has short pulse width and fast response detector with bandwidth of 1GHz. Using our available laser ultrasonics system with our high response time APD detector, we could measure 0.5 mm thick aluminum sample. Despite the center frequency of 23 MHz, the signal contains broad optical side bands as well. The unipolar stress signals in ablation regime have strong

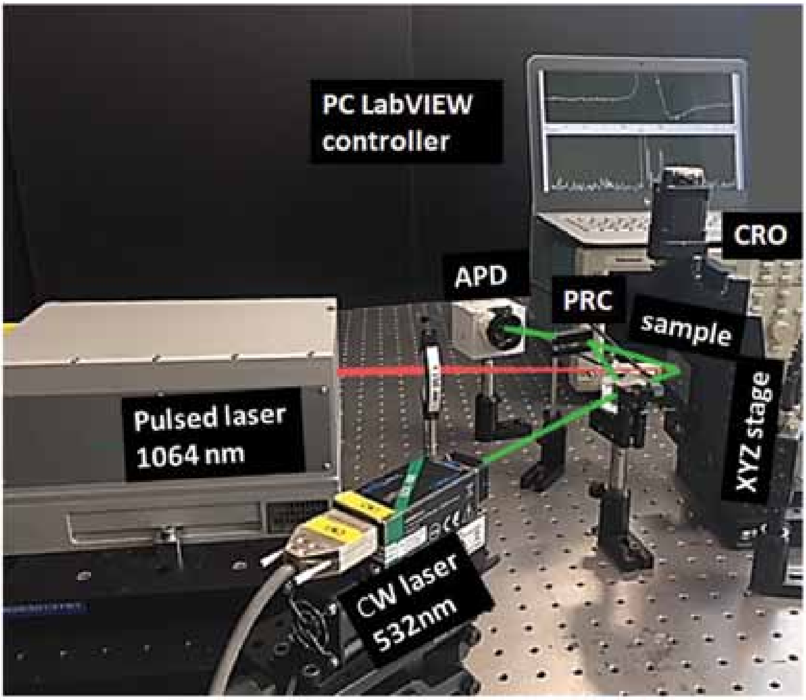


FIGURE 1
Integrated laser ultrasonic system in reflection mode.

low frequency components thus allowing low frequency ultrasound waves to propagate at longer distances such as thicker (60 mm) samples without much attenuation. Thus, this laser based ultrasonic detection system has a unique advantage with higher sensitivity on rough surfaces, better spatial resolution and more tolerance to the industrial vibrations and object motions.

3 RESULTS AND DISCUSSION

3.1 Problems associated with signal detection in the reflection method

Figure 2a shows the acquired ultrasound signal for thickness measurement in transmission mode. The waveform shows higher amplitude signal with multiple echoes. In the reflection mode, the same laser ultrasonic system is used with similar experimental conditions as in transmission mode except both beams are irradiated on the same side of the sample for generation and defect detection. There are some issues related with the interaction between the generation and detection spots that are in the adjacent regions. Mainly, the sensitivity of the surface displacement of the detection spot is distorted by the generation mechanism when two beams are kept close to each other and hence a very weak signal is observed in the reflection mode. Furthermore, the strong surface waves which propagate along the interface is interfering with the reflected longitudinal mode signal. In contrast, the surface skimming waves propagates only on the generation side in the transmission mode, hence the detection of the longitudinal mode signal is not affected by these surface waves. Therefore, some gap between the generation and detection beam is maintained to increase the sensitivity (surface roughness) of the surface displacement from the unaffected spot and also to avoid the interference by surface waves if the arrival time of the longitudinal is shorter than the surface waves.

If the detection and generation beams are kept apart with some distance over 2mm, the normal incident waves are reflected back without much deviation from the normal direction, that creates the problem of detection loss whereby the detection laser spot is away from the irradiation spot and this can be explained by the directivity of ultrasound propagation [25-26]. As the ultrasound waves generated by ablation regime are very sensitive to the incident angle, the wave propagation is mostly in the force direction. Since we used generation beam with normal incidence in order to measure actual values by the shortest propagation path, the longitudinal wave propagates in the force direction and thus multiple reflections from the rear side can reach normal to the surface. In Figure 2b, two beams are kept 2mm apart, so the first echo (T1) which is normal to the surface doesn't reach the detection spot and only slightly deviated higher order echoes would reach the detector. Therefore, an optimized distance of ~1mm is kept between the two beams without ablating the detection spot in order to increase the sensitivity, at the same time to acquire the first echo. The signal in Figure 2c shows multiple echoes including the first echo (T1) are observed which often overlaps with the tail of the strong surface waves for a sample that is 4mm thick. For the reflected signal from the defect or the rear side of thinner samples (~ 1mm), the signal will mostly be overlapped or hidden in the tail of the surface waves causing the determination of the arrival time of the ultrasound to be complicated. It is reported that to separate the longitudinal modes from the surface waves and other mode converted waves which have different acoustic velocities, a large gap is given between the two beams to maximise the difference in their arrival times. Ultimately, the signal reaches the receiver end after multiple reflections, but the signal, especially reflected from the defect has lower amplitude and minimal information can be deduced. Studies have also shown that frequency spectra analysis with hanning window is used to extract the useful longitudinal mode signals in time of flight measurements where all the modes are mixed in ablation regime. Some authors have designed directional EMAT to acquire the required laser generated ultrasound mode. Extra or the missing feature in the A scan will indicate the scattered signal from the defect in the

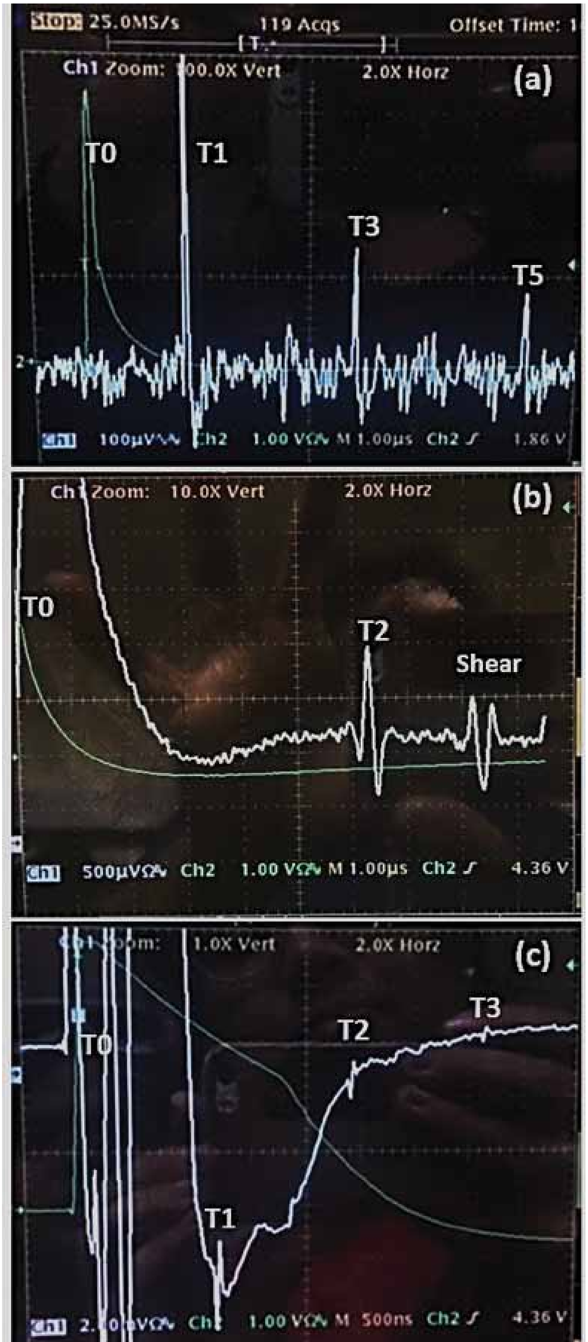


FIGURE 2
Laser ultrasonic signal from Al sample a) in transmission mode b) and c) in reflection mode, with varying the distance between two beams at 2mm and 1mm, respectively.

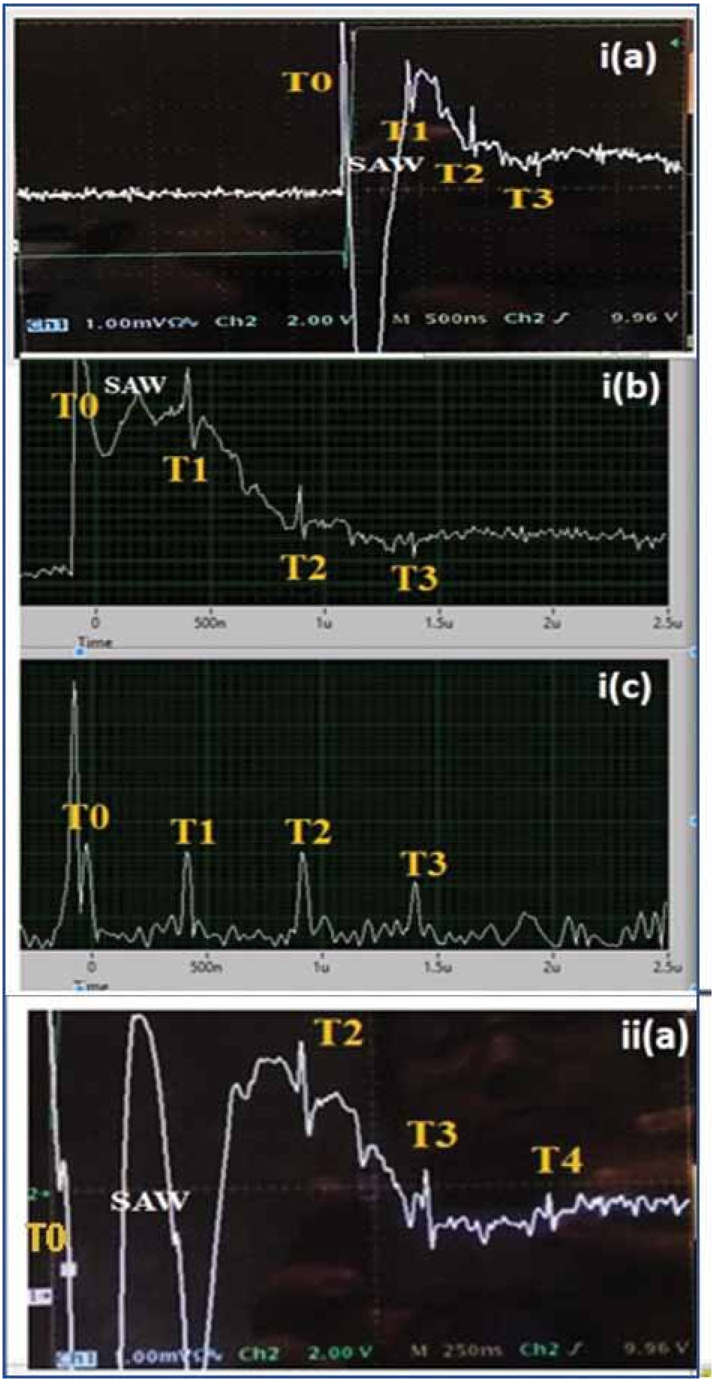
longitudinal signal. It may also be possible to detect surface breaking crack if the surface waves are disrupted. In all these cases, there was a disagreement between the line scan A and scan image B [12, 23].

3.2 Solutions to extract useful longitudinal mode signal

Utilising the property of varying frequency components of the bulk and surface waves, the desired frequency components of the longitudinal signal from the surface waves can be filtered. In most cases, the surface waves have a lower frequency distribution compared with the frequency spectra of bulk waves [12]. In practice, frequency domain analysis has been done with the original signal to determine frequency distribution and is then used with a properly designed selective filter to obtain the required signal from the low frequency surface waves. Subsequently, the inverse Fourier transform is applied to get the desired signal in the time domain to determine the arrival time of the reflected signal from the rear side and the defects for defect locations. Although frequency domain analysis would be more appropriate for some functions, such as filtering (convolutions), design systems, reconstruction of signals and reduction of noise, in a case where the signals are more likely complex and mixed, the selective band pass filter provides a longitudinal mode signal from the SAW. However, there is a possibility of the presence of some mid frequency component from the surface wave in the filtered signal. Furthermore, FFT would not give accurate information in both frequency and time domains simultaneously for waveforms like ultrasound signals that are nonlinear and non-stationary in nature. Moreover, to scan the entire sample, there is a need to set positive threshold voltage values in B and C scan, as the signal detected might have a stronger negative peak than positive in tripolar waveforms. Hilbert transform phase shifts all the positive frequency signals by $-\pi/2$ and negative frequencies to $\pi/2$ and hence it gives out an instantaneous amplitude and frequency of the component that describes the signal more locally in the time domain [27-29]. Therefore, with a selective band pass filter followed by the Hilbert transform, the phase shifting of the signal into fully positive signals by Hilbert transform helps to locate and identify the signal with an increase in instantaneous amplitude and pulse width. This is due to the combined effect of the phase shifted mono frequency components from the presence of other high frequency component of the surface wave.

3.3 Single unipolar waveforms obtained with filter followed by Hilbert transform

Comparative studies using various sequences of filtering functions with HT are carried out. Figure 3a shows the oscilloscope image of the reflected signal from a 1.5mm steel sample. Although the signal has a higher amplitude, it is overlapped with a surface wave. The subsequent waveforms in Figure 3b and Figure 3c are obtained after processing the original waveform (Figure 3a) in the oscilloscope with the Hilbert transform and filter functions in LabVIEW.


i(a)
T0
T1
SAW
T2
T3
Ch1 1.00mVΩ Ch2 2.00 V M 500ns Ch2 9.96 V
i(b)
T0
SAW
T1
T2
T3
0
500n
1u
1.5u
2u
2.5u
Time
i(c)
T0
T1
T2
T3
0
500n
1u
1.5u
2u
2.5u
ii(a)
T2
T3
T4
SAW
T0
Ch2 2.00 V M 250ns Ch2 9.96 V

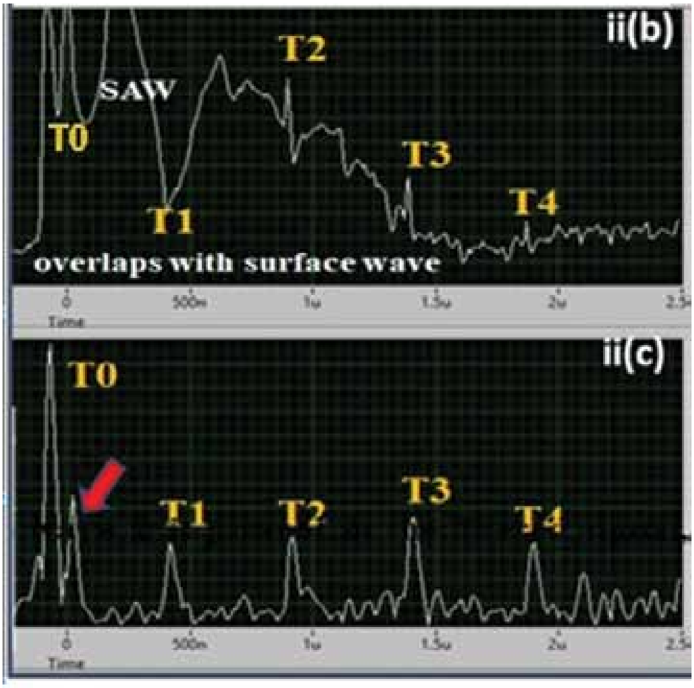


FIGURE 3
Overlapping of ultrasound signal with (i) weak and (ii) strong surface waves amplitude (a) waveform obtained directly from the oscilloscope to the labview (b) signal processing using HT only, (c) bandpass filter followed by HT.

The signal processing of the original signal using only Hilbert transform (HT) shows a clear and distinct first echo (Figure 3i(b)). Figure 3i(c) shows the signal obtained with band pass filter followed by HT. However, the signal is hidden completely in the original waveform as shown in Figures 3ii (a&b) for samples that exhibit weak reflected signal or with strong surface waves. The filtering functions followed by HT provides a distinct signal with few echoes and there is also a presence of some mid frequency component in the waveform near T0 (indicated with a red arrow in Figure 3ii(c)). This may lead to the inaccurate location of an unknown test specimen. The phase shifted positive signal from Hilbert transform increases the instantaneous amplitude and pulse width and thus helps to locate and identify the signal more easily, shown in Figure 4b. For example, a high frequency component in the waveform for the first order is at 500ns, second at 1000ns, etc. (indicated in arrow) is compared with Figure 4a in which the waveform is obtained directly from the oscilloscope to the LabVIEW without Hilbert transform. Frequency analyses using FFT are done to know the frequency distribution of the signal and

SAW waves generated using laser pulse having 8ns pulse duration, so that proper filtering bandwidth can be chosen to separate the signal. The frequency spectrum of the original signal from the oscilloscope is shown in Figure 4c. The frequency distribution of the surface wave mainly resides from 1 to 25MHz, and the longitudinal signal is between 25 to 50MHz.

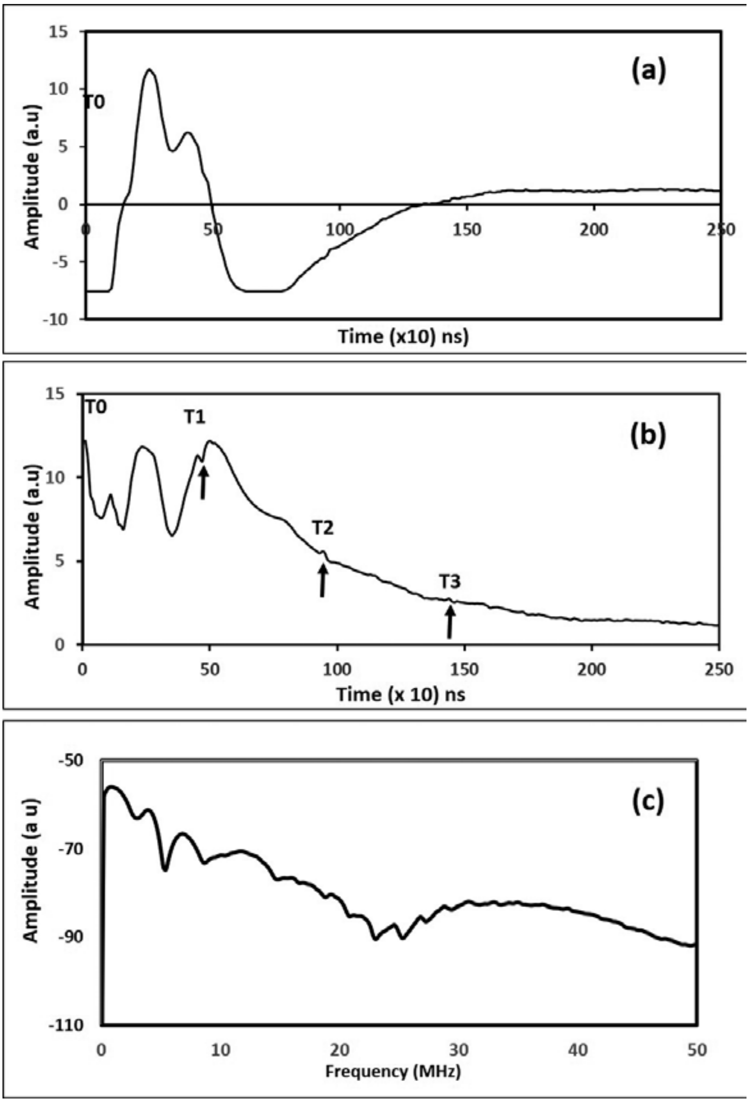


FIGURE 4
(a) Waveform obtained directly from the oscilloscope to the labview, (b) signal processing of the original signal using HT and (c) the FFT spectrum.

Systematic studies have been done with the same original signal from Figure 4a with three different sequences of filtering functions and HT. Figure 4a shows a strong amplitude from surface waves and the longitudinal signal is overlapped or hidden completely. A band pass, butterworth filter with the 3rd order is selected and lower cut off frequency is set at 25MHz and highest cut off frequency at 50MHz. In the first approach, only a filter was used to separate the signal (Figure 5a) and in the second, the Hilbert transform is applied first followed by a filter (Figure 5b), and hence both approaches separates the weak useful signal from surface waves and provides distinct ultrasound sig-

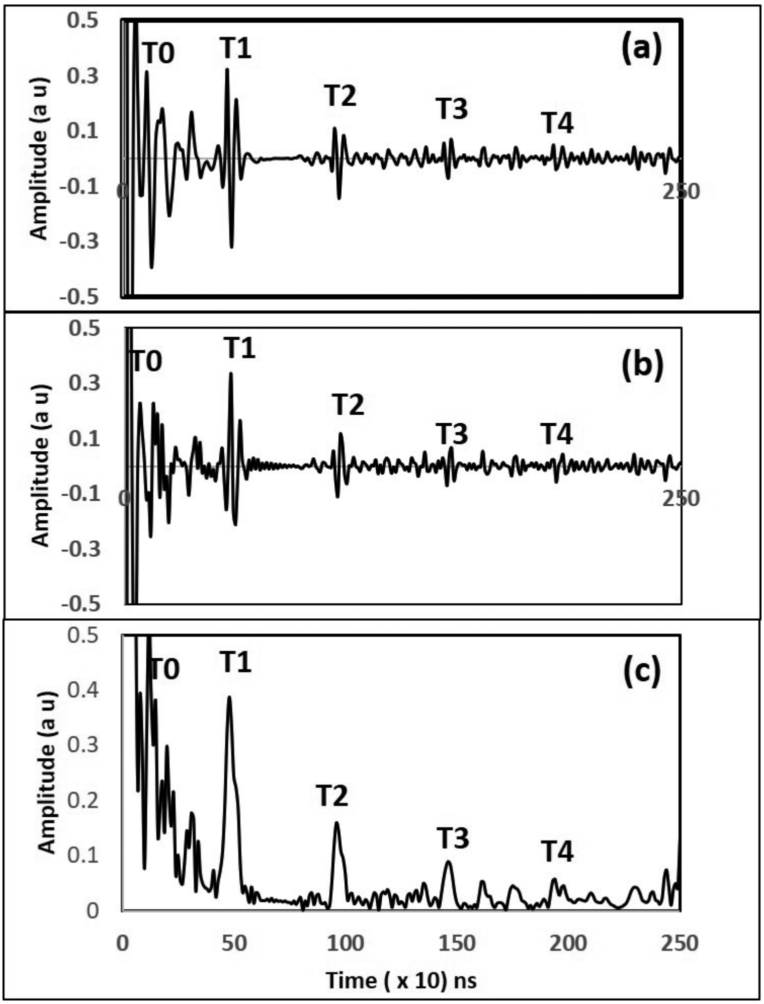


FIGURE 5
Comparative studies of the original signal with varying sequence of filtering functions with HT. A) filter only, b) HT followed by filter and c) filter followed by HT.

nal with tripolar waveform (two positive peaks with a trough) although with high frequency noise in HT-filter combination. In the third approach, we used a filter first followed by the Hilbert transform. Hence this phase shifts all the filtered signals into a positive peak, giving one clear distinct peak with an increase in the amplitude from the rest of the high frequency noise that improves the signal to noise ratio by denoising (5c). Single, distinct, unipolar waveform is obtained with these bandpass filters followed by HT combination than with the tripolar signal. It is usual that the ultrasound signal may have only negative or week positive peak voltage, so the phase shifted positive signal by HT is essential for B and C scans where the threshold voltages are set by the positive peak values.

3.4 Acquiring signal from defect using this signal processing approach

In Figure 6i(b), despite the clear first echo in 10mm thick sample, there is an absence in the defect signal which is expected to be between T0 and T1 caused by a tendency of overlapping with SAW waves. However, with a filter followed by HT, a clear distinct defect signal is observed from the tail of the SAW, as indicated in Figure 6ii(b). The T1 amplitude is lesser, since part of the ultrasound signal is reflected from the defect. The amplitude of the signal can be increased with a low noise amplifier. Usually for denoising, filtering and compression, various signal processing techniques in time and frequency domain signals such as SIFT, wavelet transform, etc. are used. From the detailed study of the frequency spectral analysis in the ablation regime, the distribution of the spectrum is mainly dependent on the material, thickness, and laser power density and hence the frequency spectra is used to identify the defect signal [12]. Hilbert Huang transform decomposes the signal into different intrinsic modes functions in the sifting process, by separating the desired signal is applied for the ultrasonic inspection of oil pipes and highly attenuating structures using PZT [27-28]. From the frequency component of the marginal spectrum which is calibrated from the IMF modes of time domain signal, the HHT is used to determine the defect characteristics [30]. The signal processing method proposed in our studies using a filter followed by Hilbert transform phase shifts the mono frequency components in the low frequency oscillatory signal thus showing a more distinct identification of defect features from the complex signal with the presence of multimode, environmental (excitation laser intensity) and electrical noises and multiple reflections from the interfaces.

4. CONCLUSION

We have successfully extracted the useful longitudinal mode ultrasound signal from the surface waves with filter followed by the Hilbert transform. The Hilbert transformed signal shows the instantaneous amplitude for high fre-

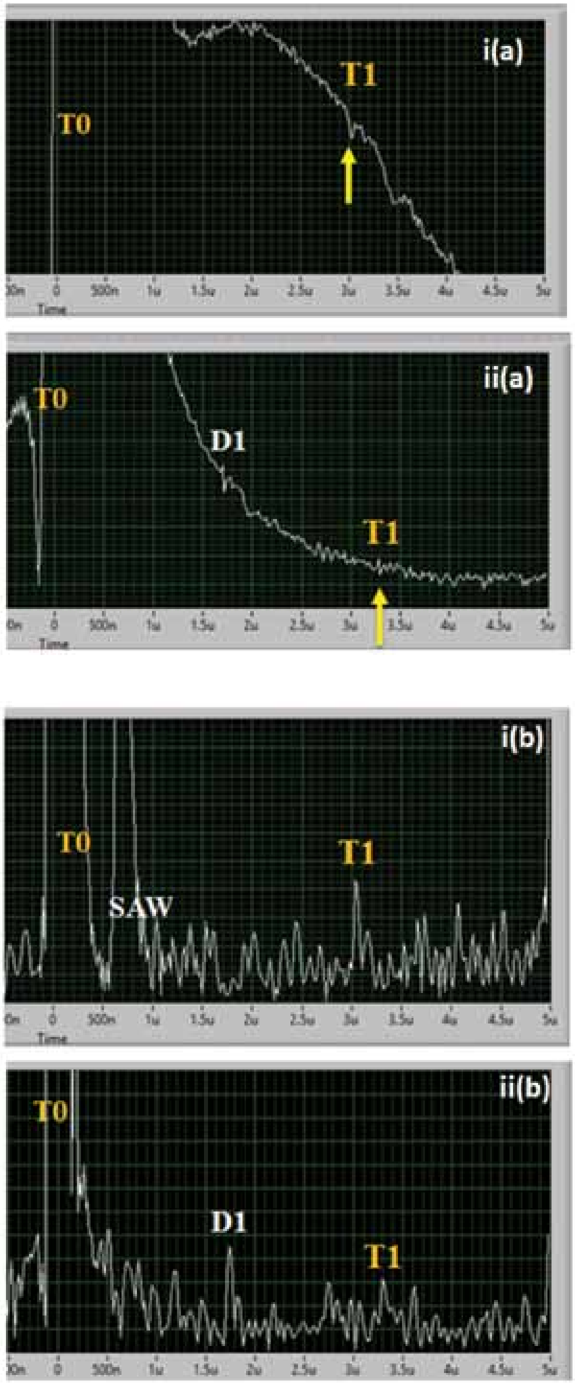


FIGURE 6
Weak defect signal observed from the tail of the surface wave with a) HT only and b) HT and filter.

quency longitudinal signal which is used as a reference to identify the desired signal with the filter. The combination of filter followed by HT gives a single positive peak with higher amplitude and improved SNR which is essential to set the positive threshold voltages for B and C scan. Integrating this signal processing method with a portable laser ultrasonic scanning system, high signal to noise ratio can be achieved without the use of a high voltage supply for the photorefractive crystal in the two-wave mixing interferometer.

ACKNOWLEDGEMENT

This research was supported by the Singapore Maritime Institute (SMI) research project (SMI-2015-OF-10).

REFERENCES

[1] Mitra M. and Gopalakrishnan S. Guided wave based structural health monitoring. *Smart Materials and Structures* **25** (2016), 053001-053027.

[2] Birks A. S., Green, Jr. R. E. and McIntire, P. *Nondestructive Testing Handbook, Ultrasonic Testing*, 2nd Edition. American Society for Nondestructive Testing, (1991).

[3] Monchalin J. P. and Wagner J. *Nondestructive Testing Handbook, Ultrasonic Testing*, 2nd edition. American Society for Nondestructive Testing, Columbus, (1991).

[4] Kozhushko V. V. and Hess P. Nondestructive evaluation of microcracks by laser-induced focused ultrasound. *Applied Physics Letters* **91** (2007), 224107.

[5] Monchalin J. P., Choquet M., Padioleau C., Néron C., Lévesque D., Blouin A., Corbeil C., Talbot R., Bendada A., Lamontagne M., Kolarik R. V., Jeskey G.V., Dominik E. D., Duly L. J., Samblanet K. J., Agger S. E., Roush K. J. and Mester M. L. Laser ultrasonic system for on-line steel tube gauging, *Review of Quantitative Nondestructive Evaluation*, *AIP Conference Proceedings* **657** (2003), 264.

[6] Kruger S. E., Lord M. and Monchalin J. P. Laser ultrasonic thickness measurements of very thick walls at high temperatures. *AIP Conference Proceedings* **820** (2006), 240-247.

[7] Scruby C.B. and Drain L.E. *Laser Ultrasonics: Techniques and applications*, UK Bristol: Adam Hilger, (1990).

[8] Monchalin J. P. Progress towards the application of laser -ultrasonics, Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12 Edited by D.O. *Thompson and D.E. bimenti, Plenum Press*, NewYork **12** (1993), 495-506.

[9] Dubois M. and Drake Jr. T.E. Evolution of industrial laser-ultrasonic systems for the inspection of composites. *Nondestructive Testing and Evaluation* **26** (2011), 213-228.

[10] Daviest S. J., Edward C., Taylor *G.* S. and Palmer S. B. Laser-generated ultrasound: its properties, mechanisms and multifarious applications. *Journal of Physics: D Applied Physics* **26** (1993), 329-348.

[11] Murray T. W. and Wagner J. W. Thermoelastic and ablative generation of ultrasound: Sound effects, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol 17 Edited by D.O. *Thompson and D.E. Chimenti, Plenum Press*, New York. 1998. 17, 619-625.

[12] Mi1 B**.** and Ume1 I. C. Parametric studies of laser generated ultrasonic signals in ablative regime: time and frequency domains. *Journal of Nondestructive Evaluation* **21** (2002), 23-33.

[13] Blouin, A. Drolet. D. and Monchalin J.P. Ultrasonic detection system based on two wave mixing in photorefractive effect. *Review of Pogress in Quantitative Nondestructive Evaluation* **14** (1995), 2245-2251.

[14] Ing R. K. and Monchalin J.-P. Broadband optical detection of ultrasound by two-wave mixing in a photorefractive crystal. *Applied Physics Letters* **59** (1991), 3233-3235.

[15] Pouet B.F., Ing R.K., Krishnaswamy S. and Royer D. Adaptive heterodyene interferometer for ultrasonic NDE. *Review of Progress in Quanticative Nondestructive Evaluation*, Edited by D.O. Thompson and D.E. Chimenti,. Plenwn Press, New York, **17**, 1998.

[16] Pouet B. F., Ing R.K., Krishnaswamy S. and Royer D. Heterodyne interferometer with two-wave mixing in photorefractive crystals for ultrasound detection on rough surfaces. *Applied Physics Letters* **69** (1996), 3782-3784.

[17] Prada C., Balogun O. and Murraya T. W. Laser-based ultrasonic generation and detection of zero-group velocity Lamb waves in thin plates. *Applied Physics Letters* **87** (2005), 194109-(3).

[18] Hess P. Surface acoustic waves in materials science. *Physics Today* **55** (2002), 42-47.

[19] Dewhurst R. J., Edwards C. and Palmer S.B. Noncontact detection of surface-breaking cracks using a laser acoustic source and an electromagnetic acoustic receiver. *Applied Physics Letters* **49** (1986), 374-376.

[20] Clorennec D. and Royer D. Analysis of surface acoustic wave propagation on a cylinder using laser ultrasonics. *Applied Physics Letters* **82** (2003), 4608-4610.

[21] Zamiri S., Reitinger B., Bauer S. and Burgholzer P. Converging Laser Generated Ultrasonic Waves using Annular Patterns Irradiation. *3rd International Symposium on Laser Ultrasonics and Advanced Sensing IOP Publishing Journal of Physics: Conference Series* **520** (2014), 012001.

[22] Jacobs L. J. and Whitcomb R. W. Laser generation and detection of ultrasound in concrete. *Journal of Nondestructive Evaluation* **16** (1997), 57-65.

[23] Dixon S., Edwards C. and Palmer S.B. A laser–EMAT system for ultrasonic weld inspection. *Ultrasonics* **37** (1999), 273–281.

[24] Sen C. and Tie G. Ultrasonic thickness measurement for aluminum alloy irregular surface parts based on spectral analysis. *Trans. Nonferrous Met. Soc. China* **22** (2012), s323(1-6).

[25] Guo Y., Yang D., Chang Y. and Gao, W. Effect of oblique force source induced by laser ablation on ultrasonic generation. *Optics Express*, **22** (2014), 166 –176.

[26] Raetz S., Dehoux, T. and Audoin, B. Effect of laser beam incidence angle on the thermoelastic generation in semi-transparent Materials. *The Journal of the Acoustical Society of America* **130** (2011), 3691.

[27] Kazˇys R., Tumsˇys O. and Pagodinas D. Ultrasonic detection of defects in strongly attenuating structures using the Hilbert– Huang transform. *NDT&E International* **41** (2008), 457- 466.

[28] Sudheera K., and Nandhitha N. M. Application of Hilbert transform for flaw characterization in ultrasonic signals. *Indian Journal of Science and Technology* **8** (2015), 56303-56309.

[29] Grünsteidl I., Veres I. A., Roither J., Burgholzer P., Murray T. W. and Berer T. Spatial and temporal frequency domain laser-ultrasound applied in the direct measurement of dispersion relations of surface acoustic waves. *Applied Physics Letters* **102** (2013), 0111039(1-4).

[30] Mao Y., Que P. and Zhang Q. Ultrasonic thickness inspection of oil pipeline based on marginal spectrum of Hilbert-Huang transform. *17th World Conference on Nondestructive Testing*, 25-28 Oct 2008, Shanghai, China, PP 1-8.