CHARACTERIZATION OF LASER GERERATED BULK WAVES USING WAVELET TRANSFORMS AND PATTERN RECOGNITION

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Abstract

This paper deals with the generation and characterization of bulk waves in thick aluminum sample using laser-based ultrasonics. Nd-YAG laser is used for ultrasonic generation and He-Ne Laser Heterodyne interferometer is used for detection. Ultrasonic signals thus obtained are quite complicated and difficult to analyse due to different kind of waves (Pressure, Shear and Rayleigh) generated simultaneously. To generate bulk waves, a thick stepped sample of Aluminium is used. The geometry of the sample is such that the center point of each step lies on an arc of a circle. This is to ensure that the time of flight of the bulk waves is constant for all angles of incidence. The ultrasonic signals obtained with this sample are analysed using continuous wavelet transforms and then the pattern recognition is performed using Moment Invariants. Pressure waves and Shear waves are identified successfully by establishing pattern similarity at different locations within the signal. Both qualitative as well as quantitative analysis has been performed to validate the results.

This paper successfully brings out the utility of the wavelet transforms based pattern recognition technique in the analysis of complex transient signals.

1. Introduction

Determination of internal structure and material properties of an object without actually destructing or damaging the material is achieved using Non Destructive Evaluation (NDE) techniques. Among the several NDE techniques available, Laser Based Ultrasonics is gaining importance in the recent times.

In Laser based Ultrasonics (LBU), a high intensity laser beam is used to generate ultrasound in the test object. One of the biggest advantages of LBU technique is that generation and detection of the ultrasound can be made at a distance, without any physical contact with the surface of the component to be inspected and furthermore no coupling medium is required. However, Laser generation of ultrasound has the disadvantage of simultaneous generation of different waves such as shear and longitudinal bulk waves, and Rayleigh and Lamb waves, thus complicating the process of signal analysis. In the present work, the and their analysis using Wavelet Transforms in generation of bulk waves using Nd-YAG laser conjuction with pattern recognition are discussed.

Scruby and Drain [1] discussed the mechanisms of generating various ultrasonic waves with lasers and detection by using variety of laser interferometers. Laser irradiation of bulk samples leads to the generation of pressure (longitudinal) and shear waves while it leads to the generation of Lamb waves in thin plates. Arnold et al [2] measured the shear wave velocities in metals using specially designed Speckle interferometer. Pengzhi et al [3] studied the directivity patterns of thermo elastically generated ultrasound in metal with consideration of thermal conductivity. Scruby et al [4] carried out the quantitative studies on thermally generated elastic waves in laser-irradiated metals. Stankovic et al [5] proposed a new signal-adaptive joint time-frequency distribution for the analysis of nonstationary signals. It was based on a fractional-Fourier-domain realization of the weighted Wigner-Ville distribution. Wavelet analysis and the properties of different wavelets are explained by Daubechies [6] in her work. Georgiou [7] discussed tissue characterization using the Continuous Wavelet Transform in his work. The present work deals with laser generated bulk waves in aluminium and their analysis.

2. Experimental Details

Nd: YAG pulsed laser is used to generate ultrasonic waves in materials or objects to be inspected and an Optical Heterodyne laser interferometer is used to detect the transmitted acoustic signals through the material. The signals are then amplified and digitized using a Yokogawa DL1740 Digital Storage Oscilloscope (DSO). The oscilloscope is triggered using a synchronization signal from the Pockels cell of the pulsed laser. The recorded waveforms through DSO are transferred over an Ethernet interface for subsequent storage and analysis. The schematic layout of experimental set-up is shown in Fig.1 while Fig.2 shows the schematic representation of the sample. The scanning is done manually using two single axis micrometer controlled XYZ translator mounted on the Optical Test Bench.

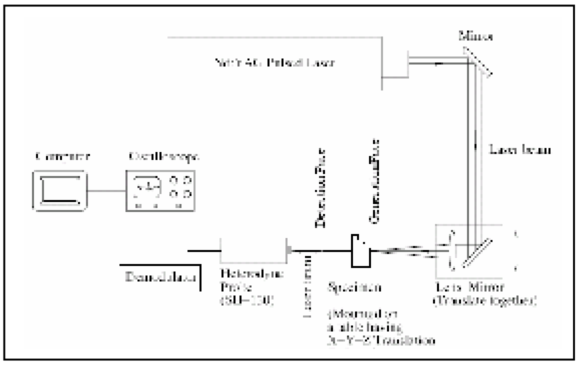


Figure 1 Experimental setup

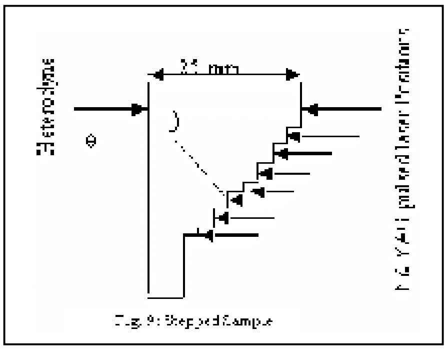


Figure 2 Stepped aluminium sample

In the experimental arrangement using laser heterodyne detection, it is necessary that the probe laser beam gets back-reflected from the surface under investigation. The heterodyne laser detects disturbances along the laser beam. If ultrasonic waves generated in the material are detected at the epicenter as shown in Fig. 3(a), one can only detect the pressure wave displacements. However, if the ultrasonic signal is picked up off-epicenter as shown in Fig. 3(b) with the probe beam normal to the surface, the heterodyne will be able to pick up the components of vibrational amplitudes of both pressure wave and shear (horizontal) wave.

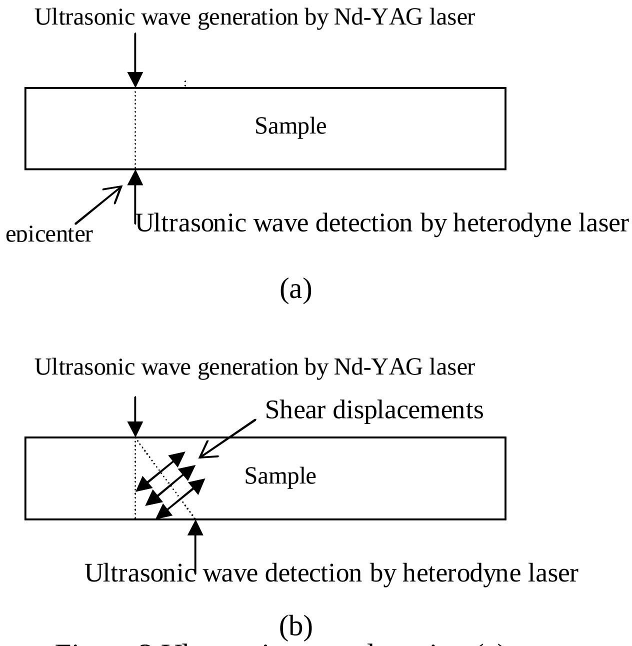


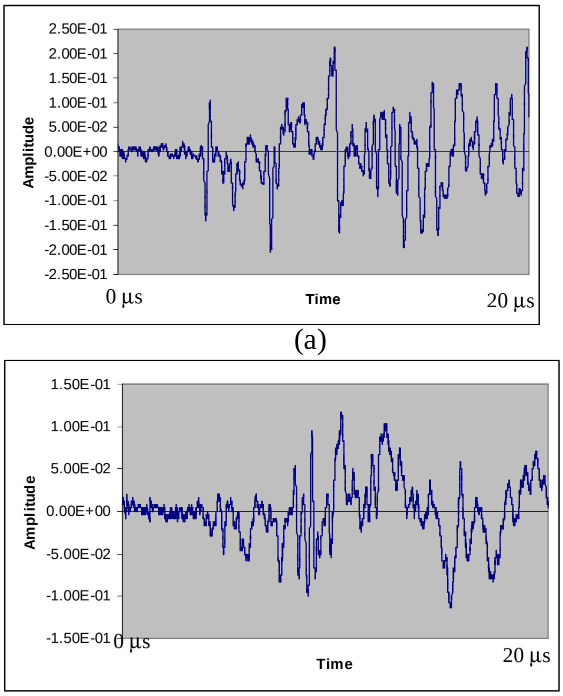
Figure 3 Ultrasonic wave detection (a) at epicenter (b) off epicenter

3. Results and Discussion

3.1 Pressure wave

The LBU signals are recorded at various positions of the heterodyne laser detector. The positions of the detector correspond to different angles between incident laser (Nd-YAG) beam and the direction of propagation of the ultrasonic wave generated inside the sample. The recorded ultrasonic signals at 0 and 40 degrees are shown in Figs. 4(a) and 4(b) respectively, while the FFTs of these signals are shown in Fig.5.

From FFT curve in Fig. 5, it is evident that the first peak in the plot is purely due to pressure wave. This is because in the present experimental configuration, at every point other than the epicenter, only a component of any wave (shear/pressure) can be detected. This fact coupled with the effect of directivity requires that the signal strength corresponding to pressure wave should decrease as the detection point is moved away from the epicenter. The variation in intensity of this peak with angle is clearly seen in this figure.



(b)

Figure 4 Recorded ultrasonic signal at (a) 0° (b) 40°

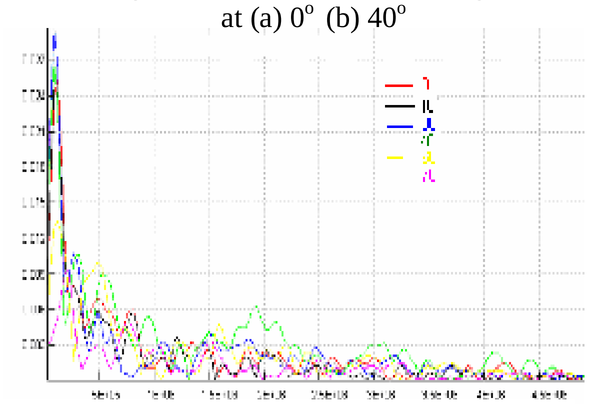
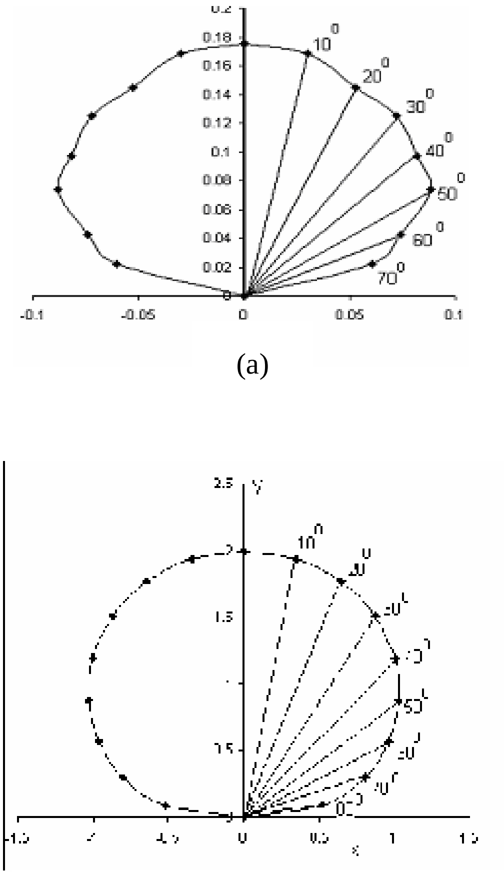


Figure 5 FFT plot of signal observed at various angles

The experimental directivity pattern is obtained from the amplitude of pressure wave observed at various angular locations and is plotted in Fig. 6(a). The theoretical directivity pattern [1] is given in Fig. 6(b). The agreement between these pattern can be seen to be quite good

3.2 Shear Wave Identification and Pattern Recognition

The identification of pressure wave is relatively simple and straightforward but such is not the case with shear wave as it gets buried in various other waves arriving at the point of detection simultaneously. So, an alternative technique is



(b)

Figure 6 Directivity pattern for pressure wave (a) Experimental (b) Theoretical [1]

needed for unambiguous identification of these waves. In the present work wavelet analysis based on wavelet transform [6,7] coupled with pattern recognition is used for this purpose.

Using wavelet analysis, signals can be characterized in both time and frequency domain simultaneously. This has proved to be a powerful tool for the analysis of non-stationary signals and it is being applied to signal analysis in a variety of disciplines, such as signal processing, image compressing etc. The transform image is plotted as Scale vs. Time. Scale is used to obtain the frequencies present at a given time with lower scale values corresponding to higher frequencies. The variation in intensities is depicted with help of various color schemes. In the present work the color code is such that the wavelet coefficients in blue represent the minimum value and those in red represent the maximum value. The red regions signify a strong presence of a particular frequency at that particular time

The continuous wavelet transform of the recorded signal at 40^0 is shown in Fig.7.

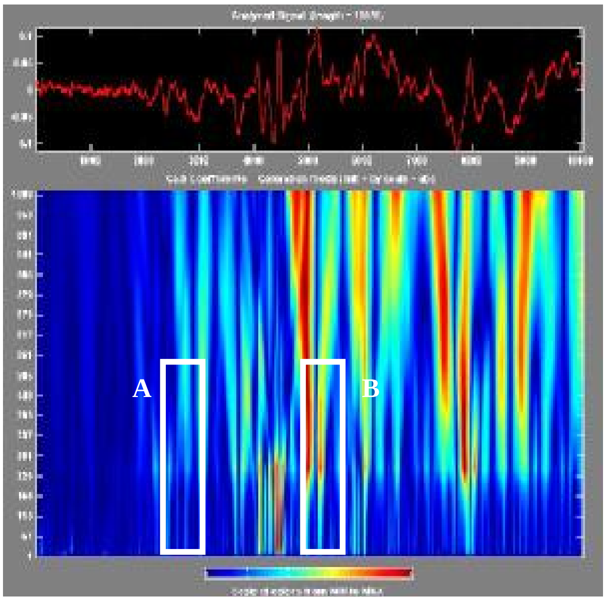


Figure 7: Wavelet transform of ultrasonic signal at 40^0

It is evident from the above figure that continuous wavelet transforms give good time-frequency localization seen by the variation in color representing how dominant a particular frequency component is at a particular time.

3.3 Pattern Similarity using Moments

3.3.1 Invariant moments

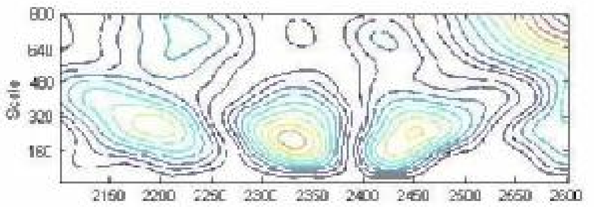
Meing-Kuei Hu [8] first introduced visual pattern recognition using moment invariants. Seven different moments are defined and these moments are shown to be invariant under translational, scaling and rotational transformation. A recognition scheme based on this moment invariance is developed for laser based ultrasonic signals to check its applicability for shear wave identification.

The central moments $\mu_{p,q}$ are defined by

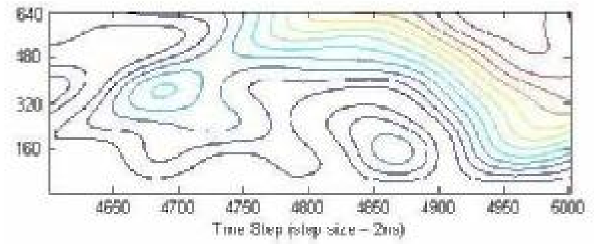
$$\mu_{pq} = \iint (x - x')^p (y - y')^q f(x,y)\,dxdy$$

where, (x', y')= centroid of a two dimensional image *f* (x, y)

In this work the wavelet transform acts as a two dimensional image. Once the complex wavelet transform of the ultrasonic signal is obtained, the wavelet coefficients are stored in a matrix. Each matrix element acts as a pixel of a 2-d image. Hence the wavelet transform of a one-



(a)



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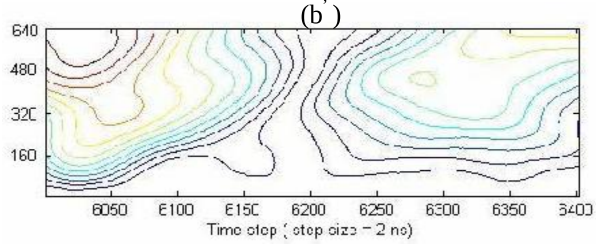
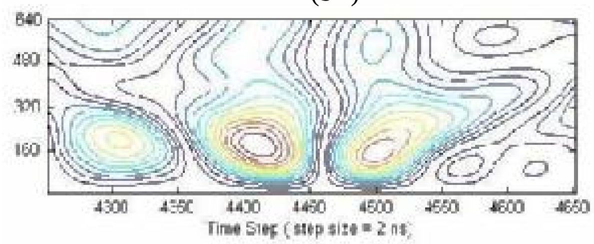


(b'')



(b''')

Figure 8: Comparison of fingerprints for (a) window A (b) for window B at random locations

dimensional ultrasonic signal is converted into a two dimensional gray level image.

Matlab code was developed to use this matrix as the source image to evaluate the moments. This method of generation of moments from a wavelet transform was successfully tested by computing the moments for a simulated image under the scaling, translation and rotation operations before applying it to an experimental signal.

Once the continuous wavelet transform is obtained, the corresponding wavelet coefficients are used for dynamic wavelet fingerprint (DFWP) generation and pattern similarity is established qualitatively. The values of moments are calculated for different regions with the help of two windows, which can be fixed at the location of interest. The calculated moments are compared for these regions.

In Fig.7 the first window (A) is taken at the location of first disturbance, which corresponds to the P-wave arrival. This location should correspond to the region of first peak in the ultrasonic signal. Second window (B) is taken at the location of interest on the time axis, which is to be compared to the window (A). Dynamic wavelet fingerprints and the corresponding normalized moments for different window locations are shown in Fig. 8 and Table 1 respectively. The qualitative comparison of fingerprints at different locations within the signals is shown in Fig.8.

The moment values corresponding to these windows are compared in Table 1. It was found that the qualitative dissimilarity in the fingerprints is corresponding to disagreement of the moment values while a good agreement can be seen between these moments when there is a similarity in the fingerprints. Thus, there is an invariance of moments whenever there is a similarity in the finger print pattern.

After studying the nature of the moments at different locations, the wave velocities corresponding to these windows are calculated. The time step at the beginning of the window is used to calculate the wave velocities using the following relation.

$$V = (d \times 10^{-3)} / (n \times 2 \times 10^{-9})$$

where, d = total wave travel distance (mm)

n = time step

Table 1: Moments for Fig. 8

Moments	I1	I2	I3	I4	I5	I6	I7
(a)	1.47	1.91	0.043	0.0081	3.8 E-05	-0.003	-0.0004
(b1)	2.0	3.70	0.60	0.010	0.35	1.13	-0.3
(b2)	1.24	1.35	0.79	0.78	0.61	0.89	-0.58
(b3)	1.42	1.69	0.025	0.010	1.3 E-05	0.007	-0.00013

The values of the velocities of the window A and window B (iii) are seen to be in very good agreement with pressure wave and shear wave velocities respectively. These values are shown in Table 2. So it can be concluded that a similarity in pattern along with invariant moments allows one to identify the shear wave location in a complex signal.

Table 2: Comparison of theoretical and experimental results (Al)

	Longitudinal Wave velocity (V_L) m/s	Shear wave velocity (V_S) m/s
Theoretical	5600-6000	2800-3000
Experimental (from pattern similarity)	5952	2941

4. Conclusions

This work provides a good tool towards simple and straightforward identification of different waves within the complex transient signal. The straightforward application of pattern recognition technique is being applied for the analysis of complex signals of LBU for the first time.

5. References:

[1] Scruby C.B. and Drain L.E. "*Laser Ultrasonics: Techniques and Applications*", Adam Hilger Bristol, Philadelphia, New York, 1990.

[2] Zhang, S.Y, Paul, M., Fassbender, S, Schleichert, U and W.Arnold., "Experimental Study of Laser-Generated Shear Waves Using Interferometry", *Res Nondestructive Evaluation*, 2, 143-155, 1990

[3] Pengzhi Zhang., Ying, C.F, and Jianzhong Shen., "Directivity patterns of laser thermo-elastically generated ultrasound in metal with consideration of thermal conductivity", *Ultrasonics*, 35, 233-240, 1996.

[4] Scruby, C.B, Dewhurst, R.J, Hutchins, D.A, and Palmer, S.B., "Quantitative studies of thermally generated elastic waves in laser-irradiated metals", *J. Applied Physics*, 51(12), 6210-6216, 1980.

[5] Ljubisa Stankovic., Tatiana Alieve and Martin J.Bastiaans , "Time-frequency signal analysis based on the windowed fractional Fourier transform", *Signal processing*, 83, 2459-2468, 2003.

[6] Daubechies, I., "*Ten Lectures on wavelets*", Philadelphia, Society for Industrial and Applied Mathematics, 1992.

[7] Georgiou, G, and Cohen, F.S., "Tissue Characterization using the Continuous Wavelet Transform; Part I: Decomposition method," *IEEE transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 48, 355- 373, 2001,

[8] Hu. M, "Visual Pattern Recognition by Moment Invariants," *IRE transactions on Information Theory*, IT-8, 179-187, 1962.