Experimental and simulated case Studies of Lamb Wave Interactions with Structural flaws and Image Reconstruction for Structural Diagnostics

Dushyantha N.D, Mrityunjaya V. Latte, Glenston Hadlee Miranda, Sayanu Pamidighantam

Abstract: The main contribution pursued in this investigation is to propose a generic optimal methodology to improve the accuracy of positioning of the flaw in a structure by reconstructing spatial image. The proposed algorithm is implemented on experimentally obtained data on Aluminum plate and simulated data on a structural steel plate. In both the cases, the data is post processed and analyzed by implementing the location identification algorithm to reconstruct the image. the proposed work uses two methods to analyze and compare baseline signals with recorded signals. Firstly before subtraction phase of recorded signal is phase corrected. In second method time windowed correlation is used to extract the signals only due to damage. Using the signal received from first method and second method the images are constructed separately and using image fusion technique new image is constructed. This algorithm improves the accuracy of positioning, estimating the shape and size of damage. The mean deviation from the actual location of the flaw to the predicted location is (1.136 mm, 0.979 mm).

Index Terms: Lamb waves, Image fusion, NDT, Time window correlation, Phase correction.

I. INTRODUCTION

There arises a need for constant monitoring of engineering structures to enable damage detection and protection from unanticipated breakdown. The process of implementing damage detection and characterization strategies for engineering structures is referred to as Structural Health Monitoring (SHM). Structural Health Monitoring is a major area of research with application potential spanning over wide range of fields such as Aerospace, Industrial, Power, National Monuments and Bridges. A definitive and conclusive prediction of imperfections, cracks, foreign precipitates, voids etc. is still very far from reality due to the multi-physics nature of the problem. Wang Bo He–Wei [1] discussed the use of frequency perturbation algorithm for damage location identification. Sarvajith et al [2] discussed fault detection of ball bearing by combining time, frequency and time-frequency domains. Ultrasonic imaging has emerged as the most promising of all NDE technologies [3] because of its high sensitivity, accuracy in determining cracks, defects and physical properties in a structure, simplicity of use, ease of application and cost effectiveness. The conventional time of flight technique [4] is not reliable for locating defects even in isotropic plates. The use of Lamb wave has recently been interested in non-destructive evaluations for thin plate structures [5, 6, 7]. In contrast to these classical techniques using longitudinal wave, Lamb wave has the advantage of propagating over a large distance thus inspecting the entire specimen including inaccessible portion of the objects. Variation of the Lamb wave velocity however causes difficulties for interpretation of the observed signals [8]. Several developments in the past have greatly helped to enhance ultrasonic detection and sizing. In most of the existing imaging algorithms base line signals are subtracted from the recorded signals from structure to be tested, because of dispersiveness of Lamb wave, environmental changes and improper positioning of sensors can cause the phase to change[9]. In this paper image is constructed using two methods, in first method damage is imaged by analyzing the signal using phase correction method, in second method time windowed correlation is used. The images constructed using first and second methods are fused using Discrete Wavelet Transform (DWT) fusion techniques. This paper is organized as follows in Part II we briefly present the transient pressure acoustic model using COMSOL 4.2 a multi-physics FEM tool**,** Part III discusses about experimental details, Part IV signals are analyzed and image is constructed using phase correction method, Part V discusses about time window based cross correlation for analyzing the signals and image construction, Part VI discusses about image fusion techniques, Part VII conclusions and future work.

II SIMULATED TRANSIENT PRESSURE ACOUSTIC MODEL

Using COMSOL 4.2 a 2D transient pressure acoustic model is created, which consists of a 50 mm x 50 mm

Manuscript received on July, 2012.

Dushyantha N.D, Electronics and Communication Engineering Department, S B M Jain College of Engineering, Bangalore, India,

Dr. Mrityunjaya V. Latte, Electronics and Communication Engineering Department , J.S.S Academy for Technical Education, Bangalore, India

Glenston Hadlee Miranda, Electronics and Communication Engineering Department, P.E.S Institute of Technology . Bangalore, India.

Dr. Sayanu Pamidighantam, Telecommunication Engineering Department, P.E.S Institute of Technology . Bangalore, India.

structural steel plate with four acoustic transceivers 90 degree apart as shown in fig 1a each providing 5cycles sequential Sinusoidal excitation placed along its perfectly reflecting boundary. Further, from the sequential excitation of each point source the received acoustic signals are collected from all the receivers including the reflection towards the source. The signals received at points 1,2,3&4 are plotted against time as shown in Fig1b.

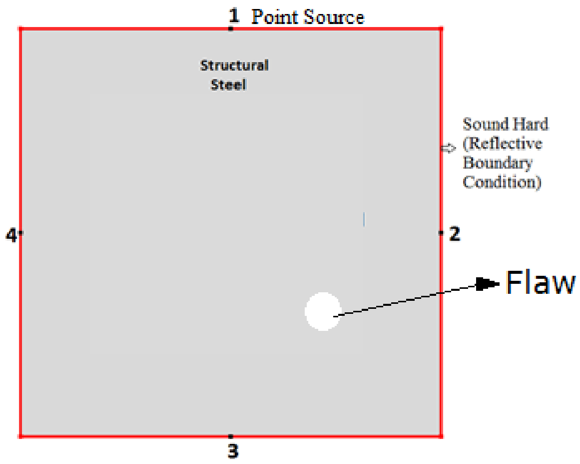


Fig 1a. Geometry of the Steel structure with its transceivers and the flaw positions

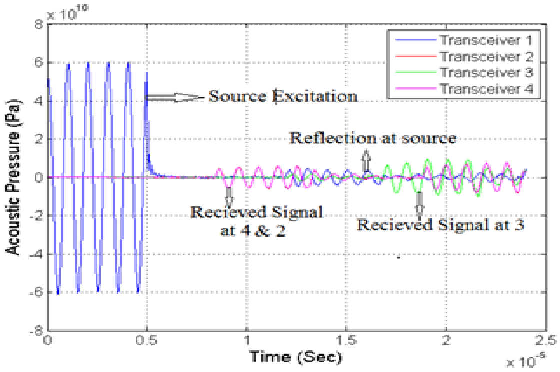


Fig 1b. The pressure field at transceivers 1,2,3&4 plotted against time

Propagation of sound waves in the domain is described by the Helmholtz wave equation:

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2}-\nabla\frac{1}{\rho}(\nabla p)=Q \qquad (1)$$

where, p is the acoustic pressure (Pa), ρ is the density (Kgm^{-3}), Q is the monopole source strength(m^2s^{-2})and c is the longitudinal speed of sound (ms^{-1}). The incident ultrasonic wave is modeled as a flow point source present in COMSOL.

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2}-\nabla\frac{1}{\rho}(\nabla p)=\frac{\partial S}{\partial t} \qquad (2)$$

Sound Hard Boundary condition is applied along the four sides of the plate described by the following equation.

$$\frac{\partial p}{\partial n}=0 \qquad (3)$$

This boundary condition ensures that the normal acceleration to the boundary is zero. Maximum element size is selected according to the following equation $\Delta max=c/(N_{ew}f_{max})$ [10,11] where c is the velocity, As per CFL (Courant Friedrichs Lewy) criteria, the critical time steps to be used for simulation on FEM model for a time dependent solver is Δ_{max}/C_L.

III EXPERIMENTAL DETAILS

To understand the damage detection using Lamb waves experiments are conducted on Aluminum plates of size 300 mm x 300 mm x 3 mm with an array of 8 PZT placed on plate as shown in Fig 2. The distance between Transducers was 80 mm, were triggered using Supertex MD1213, the signal was received by the other set of transducer the output was connected to the digitizer PXI-5105. signals are recorded by exciting one transducer at a time and receiving signal from another set of 4 Totally 16 signals are recorded with transmitter receiver pairs(1→1, 1→2, 1→3, 1→4, 2→1, 2→2, 2→3, 2→4,3→1, 3→2, 3→3, 3→4, 4→1, 4→2, 4→3, 4→4). The signal received by receiver1 when transmitter 1 was excited with a distance between them 80 mm is as shown in Fig.3, Fig 3a shows the measured signal from a plate without any damage and Fig. 3b shows the measured signal from a plate with a hole of 5 mm diameter.

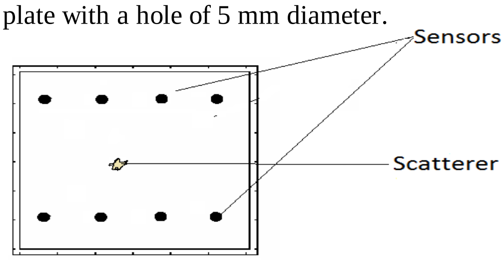
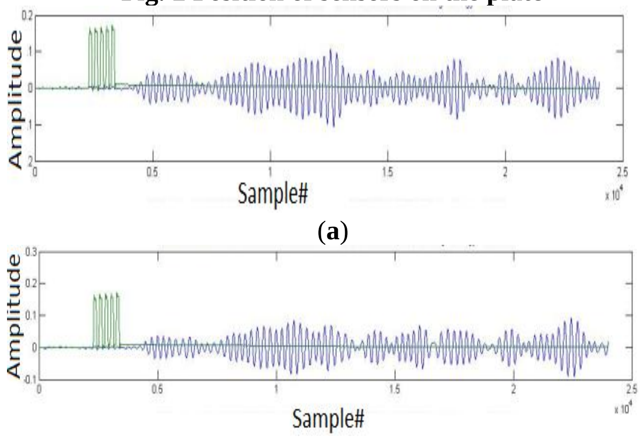


Fig. 2 Position of sensors on the plate



(a)

(b)

Fig. 3. (a) Signal from structure with flaw (b) Signal from structure without flaw

IV IMAGE CONSTRUCTION USING PHASE CORRECTION METHOD

In active health monitoring a Lamb wave signal excited in a plate with a central frequency ω_0 and transducers are located as shown in Fig.2. Assuming plate is homogeneous and isotropic with M identical transducers, signals are obtained generating ultrasonic wave with one transducer and by recording the response with multiple receivers; this process is repeated with different transducers as the transmitter. nf_{ij} is the base line signal received by the receiver j by the excitation of transmitter i and f_{ij} is the signal from damaged structure.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

If there are M transducers there are M(M-1) combinations of signal interrogation possible. In this work, array size of 8 are chosen, therefore 56 combinations are possible, due to reciprocal theory i.e $f_{ij}=f_{ji}$ only 16 signals are considered. Because of dipersiveness, environmental condition and improper positioning of transducer the phase may change as shown in Fig 4a. Therefore effectiveness of subtraction process reduced, it needs to be phase corrected before subtraction.

Let $f_{ij}(n)$ and $nf_{ij}(n)$ are the discrete-time signals received from the plates with damage and without damage respectively and .

$nf_{ij}(n) = f_{ij}(n-D)$ n=0, 1 , ……….N-1 (4)

N is the number of samples and D is the difference in arrival time. After finding the phase angle[12] the phase of f_{ij} is adjusted to match with nf_{ij} as shown in Fig.4b.

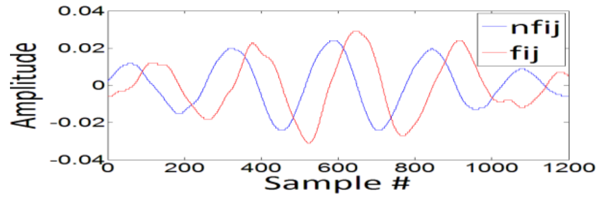


Fig.4a Signals before phase correction

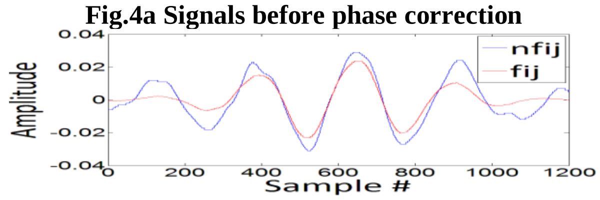


Fig. 4b Signals after phase correction

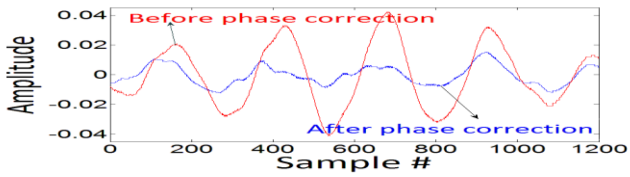


Fig.4c Difference signal $df_{ij}=(f_{ij}-nf_{ij})$

The difference signal i.e the signal due to damage alone before phase correction and after phase correction are as shown in Fig 4c. Now using this signal spatially distributed image from each differenced signal is computed using the equation

$$S_{ij}(x,y)=\sum_{p=1}^{k}\left|df_{ij}(t_{ij}(x,y))\right| \quad (5)$$

$$t_{ij}=t_{off}+\frac{d_{ij}}{c_g} \quad (6)$$

df_{ij} = differenced signal

c_g = group velocity

K ---------- Total number of windowed signal samples

$d_{ij} = (r_i+r_j)$

$$r_i=\sqrt{(x_i-x)^2+(y_i-y)^2} \quad (7)$$

$$r_j=\sqrt{(x_j-x)^2+(y_j-y)^2}$$

(x_i, y_i) ------- Position of i^{th} transmitter

(x_j, y_j) ------- Position of j^{th} receiver

t_{off} ------- Offset time

r_i= distance between image pixel(x,y) transmitter i

r_j= distance between image pixel(x,y) receiver j

Image of the damage is obtained by superimposing the image due individual actuator sensor pair as given in the below equation, the intensity will be maximum at the position of the flaw as shown in Fig. 5. Spatial image obtained using this method is as shown in Fig.7a.

$$S(x,y)=A\sum_{i=1}^{\frac{N}{2}}\sum_{j=1}^{\frac{N}{2}}S_{ij}(x,y) \quad (8)$$

A -------------- Gain factor

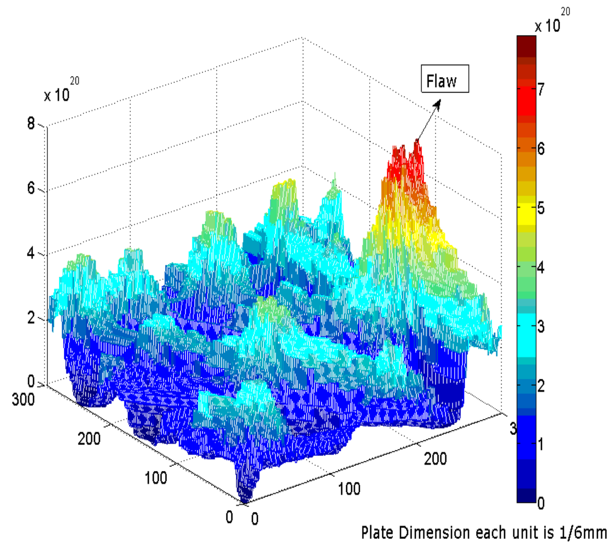


Fig 5. 3D plot of Pixel intensity

V. IMAGE CONSTRUCTION USING TIME WINDOWED CORRELATION METHOD

In this method signal is compared with the baseline signal using time windowed correlation method.

$$R_{xy}(\tau,t)=\frac{1}{\Delta t}\int_{t-\Delta t}^{t+\Delta t}x(s)\omega(s-t)y(s+\tau)\omega(s+\tau-t)ds \quad (9)$$

Where ω(t) is a windowing function and τ is the cross correlation lag time. The short time cross correlation is normalized. If the correlation coefficient is less than some threshold value the signal from undamaged structure corresponding to that window is retained otherwise make it zero as shown in Fig 6 and the spatial image obtained using is as this signal shown in Fig 7.

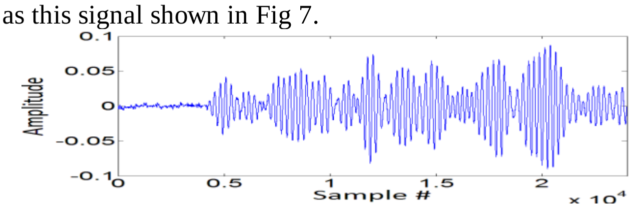


Fig. 6a signal due to damage without time window correlation

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

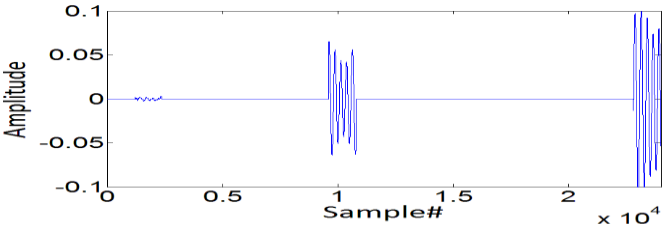
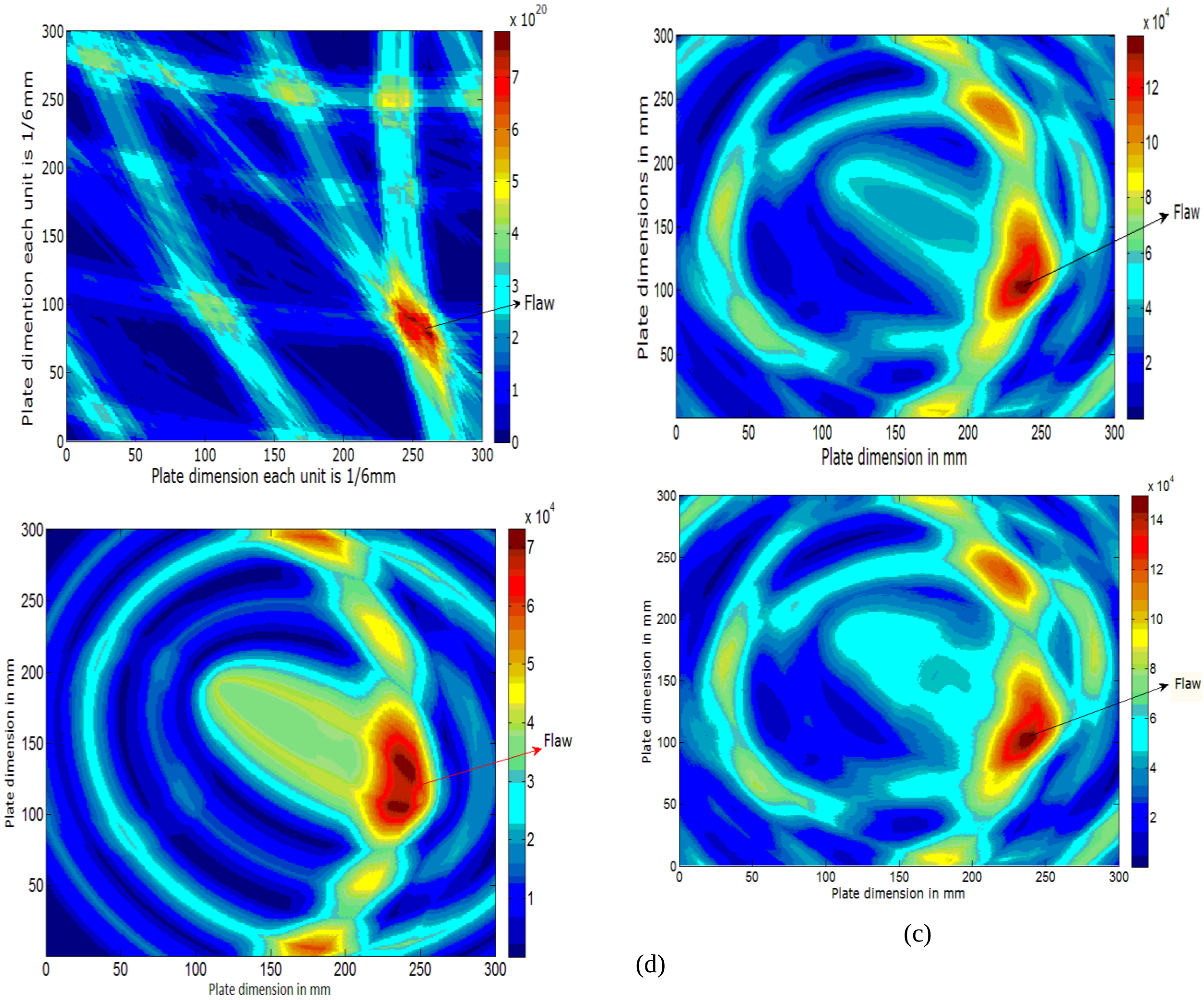


Fig.6b Echoed signal due to damage extracted using time window correlation

VI. IMAGE FUSION

Image fusion is the process of combining information from two or more images of a scene into a single composite image that is more informative and is more suitable for visual perception or computer processing [13, 14]. In this paper DWT based fusion technique is used. The principle of this method is to detect any irregularities (usually representing defects) from the NDT images and preserve them in the fused image as shown in Fig 7d.



(a)

(b)

(c)

(d)

Fig.7(a) Image of the plate with hole from simulation data using time window correlation method. (b) Image of the plate with hole from experimental data using phase correction method. (c) Image of the plate with hole from experimental data using time window correlation method. (d) Image of plate with hole after image fusion

VII. CONCLUSION AND FUTURE WORK

As contrary to many researchers belief on limitations of time domain differencing for failure, because of phase change in the signal due dispersiveness of Lamb wave, environmental changes and improper positioning of sensors. In this paper two methods are used for analyzing in time domain, the results of both the methods are found significant because they demonstrate effective damage detection, localization and characterization as applied to both complex signals and changing environmental conditions. With this proposed technique there is a mean deviation of (1.136mm, 0.979mm) from the actual location of the flaw to the predicted location. Image is reconstructed and it matches well with the predicted coordinates by geometry. Future work includes study of the acoustic signature of the flaw with the material being anisotropic.

The shape, size and position of multiple flaws in the structure need to be considered as well as the life prediction of the structure and the adverse effects that the flaws have on the structure.

REFERENCES

1. Wang Bo He-Wei, “A new method based on matrix perturbation and improved residual force vector for structural damage detection”, IEEE International Conference on Computer Science and Information Technology, 8-11 Aug 2009, pp. 61-64
2. Sarvajith M, BrijeshKumar Shah, Dushyanth. N .D, S. Jana “*A Novel Approach for Bearing Fault Detection and Classification using Acoustic Emission Technique* ”, Proceedings of International Conference on Advances in Computer Science and Electronics Engineering - ICACSEE 2012, Mumbai India 25-26th March, 2012.
3. Mix, P. Introduction to Non-Destructive Testing – A training guide, New York, John Wiley & Sons (1987).
4. L. Satyanarayan, **C.V. Krishnamurthy**, K.V. Mohan, K. Balasubramaniam, Simulation of ultrasonic phased array technique for imaging and sizing of defects using longitudinal waves, International Journal of Pressure Vessels and Piping, vol. 84, pp 716-729, 2007.
5. Satyarnarayan, L., Chandrasekaran, J, Maxfield, B., & Balasubramaniam, K. (2008). Circumferential higher order guided wave modes for the detection and sizing of cracks and pinholes in pipe support regions. NDT & E International, **41(1)** 32–43 (2008).
6. Michaels, J. E. Detection, localization and characterization of damage in plates with an in situ array of spatially distributed ultrasonic sensors. Smart Materials and Structures, *17*(3), 035035. doi:10.1088/0964-1726/17/3/035035, (2008).
7. Su, Z., Ye, L., & Bu, X. (2006). A damage identification technique for CF / EP composite laminates using distributed piezoelectric transducers. *Composite Structures*, *57*(2002), 465-471.
8. Victorov, Rayleigh and Lamb Waves: Physical Theory and Applications_Plenum, New York, 1967
9. N.D. Dushyantha, Mrityunjaya V. Latte and Sayanu Pamidighantam “Two Dimensional Spatial Fusion Technique for Imaging of Damages in Plates using Lamb Waves” Proceedings of *Third International Conference on Sensors and Related Networks (SENNET-12), VIT University, Vellore, India. Jan. 19-21, 2012. pp.206-209.*
10. Bikash Ghose, Krishnan Balasubramaniam, C V Krishnamurthy and A Subhananda Rao “ Two Dimensional FEM Simulation of Ultrasonic Wave Propagation in Isotropic Solid Media using COMSOL”, COMSOL Conference, 2010, India.
11. Soumya P.S, Dushyantha.N.D, Surabhi K, Vinay Krishnappa, Glenston Hadlee Miranda “Investigation of acoustic structure interaction for flawed structure” Proceedings of International Symposium on Physics and Technology of Sensors University of Pune, India 8-10 March 2012,
12. So, H. C., Ching, P. C., Ho, H. C., & Chan, Y. T. A novel constrained algorithm for delay estimation in the presence of multipath transmissions. *IEEE International Conference on Acoustics Speech and Signal Processing*, 313-316 vol.1. Ieee. doi:10.1109/ICASSP.1993.319118, (1993).
13. Tania Stathaki, Image Fusion: Algorithms and Applications, Academic Press (2008)
14. W.K. Pratt, `Digital Image Processing', Wiley, Third Edition (2001).