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Weld Flaw Detection Using Various Ultrasonic Techniques: A Review

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Abstract: In order to obtain the quality and safety in industrial applications (Oil industry, Utility generating company, Chemical Plants, Nuclear Power Plant, Prototype Fast Breeder Recorder, etc.,), the damaged products must be identified. This can be achieved using Non Destructive Testing. That is, Flaw Detection is a challenging and significant task in Non Destructive Testing. Among various NDT methods, Ultrasonic Testing is a well-known NDT method for detecting the size of the defects and location of the defects in a test material. Nowadays the Ultrasonic Testing techniques are used for inspecting the materials during production than that of radiography. One of the main objectives of the digital signal processing is to improve the detect ability of the defects. This study gives a review of various ultrasonic techniques for detecting the welding defects and aims at the usage of it.

Key words: UT, WT, SSP, Pulse-Echo, ToFD, SAFT

INTRODUCTION

A branch of material science is Non Destructive Testing. The concept of finding flaws without destroying the material i.e., without making any damage in the functional properties or characteristics of the component, material, or system, the flaw can be detected using NDT. Commonly used traditional methods are Eddy-current testing, Electromagnetic testing, Liquid Penetrant testing, Low coherence interferometry testing, MPT, Optical testing, RT, Thermo graphic testing, Visual testing and UT. These are used to detect and evaluate flaws or internal discontinuities or leaks in a system. Flaw Detection is the one of the areas wherein NDE is frequently used. It is widely used in many applications such as Aircraft machine frames, Automobile Industry, Boilers, Building and Bridge constructions, Furniture's, Pressure Vessels, Railway wagons, etc (Singh and Udpa, 1986).

The process of joining of similar or dissimilar metals by the application of heat is known as metal joining process. Metal Joining Process is divided into Brazing, Welding and Soldering. Welding is a process of joining two similar metals by the application of heat. Based on Pressure and Filler metal, the welding process is divided into two types and they are Pressure Welding (Plastic welding) and Non-Pressure Welding (Fusion welding). Arc welding, MIG welding and TIG welding are Fusion welding types. Butt, Projection, Seam and Spot are Plastic or Resistance Welding (Singh and Udpa, 1986).

Porosity, Slag and Planar defects (Cracks, In Complete Penetration etc.) i.e., Surface planar flaws, subsurface planar flaws, Laminar flaws etc., are known as weld defects. The weldment must be inspected for weld defects using NDT methods. Based on this test, weldment is to be accepted or rejected and the quality of the weld is also to be determined. In a good weld, these tests would indicate a lack of flaws. Some of the objectives of the digital signal processing are to generate information about processes such as welding, the remaining life of material structures, to improve inspection reliability etc., (Singh and Udpa, 1986). Now Let us see how the flaws in the weldment can be detected using various techniques of ultrasonic testing.

Ultrasonic testing: Using the sound wave's frequency, the sound wave is divided into three. First one is Infrasound wave whose frequency is less than 20 Hz. Second one is Audible wave whose frequency lies between 20 Hz to 20 kHz. And third one is Ultrasonic wave or ultrasound whose frequency is greater than 20 kHz. In UT, very short ultrasonic waves with center frequencies are passed into the test specimen to detect the presence of flaws, to find the characteristics and thickness of the test material. UT techniques are used to detect both inner (sub-surface) defects and surface defects in structural materials (Doyle and Scala, 1978). Ultrasonic testing is done on alloys, concrete, composites, Austenitic stainless steels and other metals,

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Table 1: Comparison between through transmission and pulse echo methods

SNO	Through transmission method (attenuation mode)	Pulse echo method (reflection mode)
1	Utilizes the transmitted part of the ultrasonic wave	Utilizes the reflected part of the ultrasonic wave
2	Probes are on the different sides of the material	Probes are on the same side of the material
3	Does not give the depth i.e., location of the defect	Gives the location of the defect
4	Two probes used-each on opposite sides of the material	Either one or two probes used If two probes-both on the same side of the material

etc., UT is one of the tools in the NDT used to detect flaws in all the areas. UT is a widely used testing techniques to detect the presence of flaws in a test material (Krautkramer and Krautkramer, 1977; Yee and Couchman, 1976). Since design complexities are increased, in NDE, Quantitatitative techniques are developed rather than Qualitative techniques (Doyle and Scala, 1978).

The principle of NDT is whenever there is a change in test material, then the ultrasonic waves will be reflected from the material. Since the flaws can be detected without destroying the material, it is called as NDT. In UT, an ultrasound probe is used to generate ultrasonic waves. The couplant such as Grease, Oil, Water, etc., is used to remove all air from between the face of the probe and the test material surface. To receive the ultrasound waveform, basically two methods namely Pulse Echo method and Through Transmission method are used. In Pulse-Echo method, the probe acts as both transmitter and receiver. The probe emits short ultrasonic pulse waves and receives the reflection of pulse waves back to the device (Manjula *et al*., 2012). The reflected ultrasound pulses come from flaws of the material or bottom surface of the material. An instrument like Oscilloscope is used to show the signal as the resultant. Distance and amplitude are used to represent the arrival time of the reflection and intensity of the reflection respectively (Manjula *et al*., 2012). In through-transmission method, a transmitter transmits sound through one surface and the transmitted sound is received by the receiver probe in the opposite side of the test specimen. If any discontinuities lie in the material between the probes i.e., in the beam path, then the receiver probe finds a decrease in the received signal's intensity, hence enlightening their presence (Manjula *et al*., 2012). The efficiency of the method is increased using couplant. The comparison between the through transmission method and pulse echo method is given in Table 1.

For weld inspection, Ultrasonics was introduced as a NDT technique in 1990's (Ditchburn *et al*., 1996). ART, Acoustic Microscopy, EMAT, IRIS, LUT, Phased Array, Projection Scan, TOFD, SAFT, SSP etc., are known as various Ultrasonic techniques. The following DSP techniques are used to improve SNR for having increased flaw detection capabilities (Chiou and Schmerr, 1991) and used to analyze ultrasonic signals (Abbate *et al*., 1997). Signal Averaging, Beam Forming, Frequency Agility, Matched Filtering, Moving Window Detector, Random Signal Correlation techniques, Auto and Cross correlation, Spectral correlation, Autoregressive analysis, Neural networks, etc., In Ultrasonics, to determine the defect characteristics, the imaging techniques ToFD and SAFT are to be used in industrial applications; to identify defect type the pattern recognition methods namely ALN and FLDA are to be used (Singh and Udpa, 1986). Time Domain waveform characteristics, the measurements of ToF, Time Domain Amplitude ratios, Frequency Domain Amplitude ratios and FSA are used to recognize the signal features (Chiou and Schmerr, 1991). Based on the amplitude of the reflected ultrasonic signal, the conventional UT methods of a material correspond to the following stages: (1) Detection and Localization, (2) Characterization and defect sizing, etc., (Corneloup *et al*., 1994).

ULTRASONIC TESTING TECHNIQUES

Since flaw detection seems to be a promising area, before applying Ultrasonic Testing techniques to Flaw Detection, De-noising (Praveen *et al*., 2012) i.e., Noise Reduction (Manjula *et al*., 2013) is very important to locate the existence of flaws. The existence of flaws can be detected by the changing properties of ultrasound propagation (Silk, 1977). Here, the various ultrasonic testing techniques are discussed in this section. Ultrasonic techniques may be of Contact type or Immersion type. In contact type, the probe is placed in direct contact with the material using couplant. In immersion type, a waterproof probe is placed at some distance from the material.

Digital correlation flaw detection system: The authors (Lee and Furgason, 1983) have used paired pseudo-random codes. These are named as complementary golay codes. This system gives optimal correlation detection over wide range of SNR_I conditions and operating speeds than the earlier single probe correlation FDS. Golay codes used to beat the self-noise problem that results from incomplete pulse compression in the process of correlation. It gives improved performance in the presence of grains higher operating (scan) speed than the earlier single probe correlation FDS.

Conventional pulse Echo method: Total reflected energy is used to detect the defects. It is effective for detecting small internal flaws. But it gives poor details about the shape and size of the defect (Lam and Tsang, 1985).

Advanced techniques: Acoustic Holography or Phased Sequential Arrays are giving improved defect imaging. These techniques are limited in practical applications, because of its difficulties in operation and high equipment cost. One more approach is through the analysis of diffracted signals form insonified defects. The diffracted signal is analyzed either in time domain or frequency domain (Ultrasonic Spectroscopy) (Lam and Tsang, 1985). Based on ultrasonic image, a new algorithm was proposed by the authors Corneloup *et al.* (1994) which combines spatio-temporal condition and permits the detection of small-sized defects in austenitic stainless steel welds. This algorithm ensures the detection of the defects with large dimensions or the defects located outside the weld.

Ultrasonic time of flight diffraction method: Maurice Silk first discovered ToFD in the year of 1974 and is used to detect, size and to locate the defects. Whenever ultrasonic wave incidents on a defect, the wave reflects, transmits and also diffracts at the tips of the defect. The energy of diffracted wave spreads over a wide angle and it can be picked up from the test specimen's surface. The measurements of the time difference between the diffracted waves from the tips of a defect are called TOFD technique. Since, the diffraction takes place in space and its reception takes place in time, it is known as ToFD (Baskaran *et al.*, 2006).

Merits of ToFD: Inspection Speed of ToFD is high. It has high accurate defect sizing. The authors Subbaratnam *et al.* (2006a) proposed that it has faster scanning times and used for quantitative characterization with better accuracies.

Advantages of ToFD over X-ray technique (Mondal and Sattar, 2000):

- High POD and Cost effectiveness for wall thickness >25 mm
- Because of free radiation, it provides safety and protect the environment

Differences between ToFD and other UT methods (Mondal and Sattar, 2000):

- Instead of reflected ultrasonic energies, ToFD uses diffracted energies from the defect tips (Mondal and Sattar, 2000) i.e., diffracted energy of defect tips is measured in ToFD; but in other UT methods, total reflected energy is taken (Charlesworth and Hawker, 1984). The comparison between Pulse Echo ultrasonic technique and ToFD is given in Table 2

Table 2: Comparison between pulse echo ultrasonic technique and ToFD

SNO	Pulse echo ultrasonic technique	ToFD
1	Not provide any signs of defects	Provides the signs of defects
2	Precise calibration of the amplitude is mandatory	Not mandatory
3	No signal is received from the defect	Signal is received from the defect and measured it
4	With angular probes cannot determine the defect size	It can determine the defect size
5	Defect detection is dependant on the defect orientation	Defect detection is not dependant on the defect orientation

Ultrasonic one-skip ToFD: Because of mode conversion, the shear wave is generated in ultrasonic ToFD method using longitudinal wave. Detection of flaws near the surface (<10 mm from the surface) is not easy task. Since, flaw indications are hidden in the lateral wave, 1Skip ToFD method and Signal processing is used to detect flaws near the surface.

Conventional ToFD using longitudinal wave: To find and dimension the flaw, it uses the pulse transit time. The roughness of the test specimen's surface, orientation of the flaw, transparency of the flaw and etc., are some of the parameters used to influence the amplitude of the reflected pulse. When considering these parameters, accurate flaw sizing may be obtained. ToFD technique was introduced as a suitable defect sizing ultrasonic NDE technique. This technique is limited to thickness is greater than 15 mm sections and thickness less than 5 mm from the scanning surface. The demerits of conventional ToFD are (1) Near Surface Defects are overestimated and (2) Used for thick sections only.

In B-scan image, the echo of the longitudinal diffracted wave cannot be detected. Since the spacing between Back wall Longitudinal reflected wave and Lateral wave is small in thin sections. But from the flaw, the temporal spacing of shear wave signal is to be observed and ToF to be measured using B-scan image.

Shear wave ToFD: Both longitudinal or compressional diffracted wave and transverse diffracted wave will be generated whenever a longitudinal incident wave front meets the flaw in the test specimen. Since, the velocity of longitudinal wave (L) is twice the velocity of shear wave (S), L reaches the receiver first followed by S. In s-ToFD, ToF measurements and accordingly flaw sizing are improved because the diffracted shear wave's velocity is smaller. The authors Baskaran *et al*. (2006) have shown the simulated result of surface crack of an aluminium sample using s-TOFD technique. In the detection of defect tips, the choice of transducer frequency plays a vital role. In order to do near-surface inspection, proper probe angles must be considered.

Merits of s-TOFD: The longitudinal diffraction may superimpose. Accurate measurements of ToF calculations can be obtained from the transverse wave-diffracted echo of the defect's top tip (Baskaran *et al*., 2006).

Immersion-ToFD: In thin sections, the lateral wave, diffracted waves and the back wall echo signal will be merged together. Because of this, it is very hard to recognize and size the discontinuity. The authors Subbaratnam *et al*. (2006b, 2011) proposed a new methodology to extend the application of TOFD sections down to 3 mm.

So, ToFD is used in many different ways to detect the defects.

Image segmentation-co-occurrence matrix analysis (Moysan *et al*., 1992): A 2D histogram that multiplies possibility and accuracy of image analysis is known as Co-occurrence Matrix. Using co-occurrence matrix analysis, a new segmentation method was proposed by the authors Moysan *et al*. (1992). Because of the continuity in the repartition of amplitude, the histogram of images does not allow the discrimination between defects and noise. Because of Grain noise in austenitic stainless steel welds, the detection of crack tips is very difficult. The analysis of the above matrix using threshold helps to take defects apart from the material noise. The authors found that the B-scan image analysis with the above matrix gives excellent outcomes in the segmentation of images of cracks in a weld (Moysan *et al*., 1992).

SSP versus wavelet transform signal processor: SSP is one of the ultrasonic flaw detection algorithms based on Fourier Transform such as STFT (Short Time Fourier Transform). In Split Spectrum Processing, the signal's frequency spectrum is partitioned into a set of narrow band signals using overlapping Gaussian pass-band filters with different center frequencies and fixed absolute bandwidth to extract the flaw information (Abbate *et al*., 1997).

A set of wavelet basis functions achieved by scaling and translation of a mother wavelet is known as WT. WT is used to find the flaw and to suppress the noise. Because of the multi-resolution analysis property of wavelet transform, it gives a better resolution than that of STFT. WT is used to get better detection of flaws in noise affected signals. Here relative bandwidth is constant. For identifying flaw echoes from the background noise, MRA property of WT is used (Abbate *et al*., 1997). Sub-band decomposition is also possible in DWT. In DWT, window is a set of scales that acts as BPF. This window is equivalent to BPF of split spectrum processing. The authors Oruklu and Saniie (2004) have found better results using higher order kernels. When the measurement of flaw-to-clutter ratio is less than or equal to 0 dB, using DWT, the authors Oruklu and Saniie (2004) achieved the flaw-to-clutter enhancement of ultrasonic signals of 5-12 dB.

Signal matching wavelet for UFD: The energy distributions of the noise and the flaw or clean echo are different in WT domain. In order to get an optimal energy match between the flaw echo and the wavelet basis, two problems (Concentration and Separation) must be solved:

Echo Signal = clean echo or flaw
echo signal+ background noise
i.e., $x(t) = r(t)+n(t)$

Here, to get a localized energy distribution of flaw echoes in WT domain, the transmitted signal s(t) is taken as a mother wavelet function W(t). The authors Shi *et al*. (2011) proved that the flaws efficiently detected using SMW even for SNR_I as low as -20dB.

Model-based enhancement of the TIFD (Jung *et al*., 2003): Deconvolution is used to define a deconvolution pattern or similarity function h (t) with the help of target signal g (t) and reference signal f (t). Technique for Identification of Flaw Signals using Deconvolution i.e., TIFD is used to find various signals. In TIFD, the number of reference signals is the same as that of the flaw types under consideration:

$$h(t) = f(t)\otimes^{-1}g(t) \tag{1}$$

If f (t) = g (t) then Eq. 1 i.e., h(t) becomes a sharp impulse-like shape or impulse-like pattern; otherwise it follows complicated shape or broad pattern. Based on deconvolution pattern shape, the type of flaw is also to be found. Instead of defining various reference signals in TIFD, only one well-defined reference signal is obtained from STB-A1 block. The authors Jung *et al*. (2003) concluded that the deconvolution pattern is dependent on the scattering mechanism. Bipolar patterns and Impulse-like patterns are obtained due to the scattering from small flaws such as crack tips, spherical voids and the simple reflection, respectively (Jung *et al*., 2003).

Acoustic Microscopy: The scanning ultrasonic or acoustic microscopy (SAM) enables to detect and locate defects. Apart from amplitude and pulse arrival time, the phase of the signal is also used. Hence, the resolution increases and it is possible to get the flaw images on B-C-or D-scan types (Ermolov, 2004).

Synthetic aperture focusing technique: To enhance image resolution and increase SNR, spatio-temporal correlation of signals is used by SAFT. If a defect is to be found at the point (x_1, y_1), then the TOF from probe to the defect is given by Eq. 2:

$$t(x) = \frac{2}{c}\sqrt{(x - x_1)^2} \tag{2}$$

Here, c-sound speed of the material. The defects have similar hyperbolic ToF locus with the different location and depth. The defect is found at the center of the locus at every scan. The hyperbolic ToF loci have only one intersection that is known as the location of the defect. When we add all the 2-D radial images from each and every scan, a peak is visible at the flaw (Liou *et al*., 2004). The authors Liou *et al*. (2004) proposed the use of SAFT for ultrasonic Flaw detection. The authors Liou *et al*. (2003) successfully detected the flaws in solid materials.

Ultrasonic phased array testing: Phased Array uses number of probes each of different angle. The sizes of probe elements are less. So its cost is high. In order to generate interference at a specific depth and a specific angle, the output pulse of every probe element is time delayed. These time delays can be incremented over a range of angles to sweep the beam over the preferred angular range (Birring, 2008). The authors Birring (2008) have found the ability of PA to detect the discontinuities of weld samples. And they have achieved 100% of detection of discontinuities.

RESULTS AND DISCUSSION

The micro structural change of the stainless steel can also be detected with the changes in backscattering noise and ultrasonic measurement of velocity (Kawashima *et al*., 1996). But Ido *et al*. (2004) used one-skip ToFD method for inspecting the material whose thickness is 10 mm (Near surface inspection). Using s-ToFD, the authors have found that the flaws which are very close to the scanning surface is improved by 20-35% than the conventional time of flight diffraction technique (Lee and Furgason, 1983). The authors proposed that the near-surface defects are to be found using 5 MHz transducer frequency and 40-50° of probe angles (Baskaran *et al*., 2006). The authors Abbate *et al*. (1997) found the improvement in detection using steel samples with simulated flaws. ToFD discussed for weld defect detection (Dijkstra and Bouma, 1996). The authors Shi *et al*. (2011) found that ToFD has been found to be more feasible to detect weld defects and thick layers of steel. The authors Prabhakaran *et al*. (2004) concluded that ToFD can be used for testing fabricated pressure vessel components rather than the traditional NDT methods. A signal processing technique based on empirical mode decomposition and the HT to get better time resolution of the ToFD signal, exact sizing and location of deeper flaws was proposed by Sinclair *et al*. (2010) and Chen *et al*. (2005). The authors Lalithakumari *et al*. (2011) have improved the efficiency of defect detection. Because of multiple scans of materials in SAFT, the authors Liou *et al*. (2004) found the images with better resolution and located the defect with the help of hyperbolic TOF loci. A new approach for detecting flaws in ToFD type ultrasonic images based on two dimensional Gabor functions and Fuzzy c-mean clustering classifier proposed by Ahmed *et al*. (2005). Applications of ToFD method for mechanical engineering for detection and dimensioning the discontinuities in the mechanical components were proposed by Bossuat *et al*. (2006). The authors Birring (2008) concluded that the output of PA image was easy to interpret for discontinuity detection and characterization than that of A-scan ultrasonic testing. The authors Charlesworth and Temple (2001) proposed the usage of ToFD to inspect materials than that of other NDT procedures. The authors Zahran *et al*. (2002) concluded that the processing techniques developed for GPR may be adapted for use with ToFD applications. The 0.245 mm is the maximum error for the 12.746 mm crack size in conventional method. But the authors Zhang *et al*. (2008) achieved 0.048 mm as the maximum error for the same crack size using ToFD based on cross correlation method. The authors Cao *et al*. (2010) proposed ToFD (B-scan ultrasonic image) based on edge detection to accurately detect the defects. ToFD imaging for double-probe reflection method is proposed by Chang and Hsieh (2002) to process the image and to detect the non-horizontal flaws.

CONCLUSION

Many ultrasonic methods and new algorithms are used to detect flaws in weldment. Based on images (B-scan, C-scan, D-scan types), SNR, Phase of the signal or diffracted signals, the detection of the flaws can be achieved. Every ultrasonic technique methods have their own advantages and disadvantages. In SMW, flaws can be detected efficiently even for input SNR is upto-20 dB. Like Acoustic Holography, it has high equipment cost. So, it is also limited in practical applications. ToFD using longitudinal wave is limited to thick sections only. To beat the difficulties with the inspection of near surfaces and thin sections using ToFD, shear wave-ToFD is used. And s-ToFD detects defects both in thin and near surfaces. i-ToFD gives a better solution to detect the defect in thin weldments. SAFT is used to enhance image resolution and improve SNR. Phased Array is also nowadays used to detect the defects using multi element transducer.

ABBREVIATIONS

BPF: Band-Pass Filter
FSA: Frequency Spectrum Analysis
HT: Hilbert transform
MPT: Magnetic-Particle testing
RT: Radiographic Testing
UT: Ultrasonic Testing
WT: Wavelet Transform
SNR_I: Input SNR

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