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Calculus of the defect severity with EMATs by analysing the attenuation curves of the guided waves

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Abstract. The aim of this paper is to develop a novel method to determine the severity of a damage in a thin plate. This paper presents a novel fault detection and diagnosis approach employing a new electromagnetic acoustic transducer, called EMAT, together with a complex signal processing method. The method consists in the recognition of a fault that exists within the structure, the fault location, i.e. the identification of the geometric position of damage, and the determining the significance of the damage, which indicates the importance or severity of the defect. The main scientific novelties presented in this paper is: to develop of a new type of electromagnetic acoustic transducer; to incorporate wavelet transforms for signal representation enhancements; to investigate multi-parametric analysis for noise identification and defect classification; to study attenuation curves properties for defect localization improvement; flaw sizing and location algorithm development.

Keywords: fault detection and diagnosis; electromagnetic acoustic transducers; EMAT; wavelet transform; non destructive testing; attenuation curves; guided waves

1. Introduction

Advances in new techniques of signal processing combined with improvements in instrumentation make Non-Destructive Testing (NDT) a reliable and effective technique for fault detection. Specifically, the signal processing methods together with Structural Health Monitoring (SHM) permit to identify, diagnose and locate the fault on the basis of changes in static and dynamic structure features (Light-Marquez, Sobin *et al*. 2011) (Márquez, Tobias *et al.* 2012) (Pliego Marugán, García Márquez *et al*. 2015) (Xu, Huang *et al.* 2015). These techniques can be implemented to be remotely controlled allowing work online, resulting in a reduction of costs attributed to failures and manual inspections, downtimes, etc. (Gómez Muñoz and García Márquez 2016) (Marugán and Márquez 2015).

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Within the SHM field, guided waves have become a particularly useful technique to inspect geometries such plates or tubes, and due its effectiveness are used in industries such as the petrochemical, gas, wind energy, aerospace and shipbuilding (Su and Ye 2009) (Zhao, Gao *et al.* 2007) (Muñoz, Márquez *et al.* 2016) (Kim, Torbol *et al*. 2013).

Guided waves technic is based on the excitation of low frequency ultrasonic waves, which can travel several meters through the material, allowing inspections of large areas without any relocation of the actuator. Novel methodologies in signal processing are being published, e.g., predictive analysis online, in order to be employed in SHM and ultrasonic waves (Gomez Munoz, De la Hermosa Gonzalez-Carrato *et al.* 2014) (de la Hermosa González, Márquez *et al.* 2015) (García, Pedregal *et al.* 2010) (Papaelias, Cheng *et al.* 2016).

The purpose of this paper is to design a novel fault detection and diagnosis (FDD) model using ultrasound inputs in conjunction with advanced signal processing methods to monitor the structural condition of a steel plate (Dai and He 2014) (García Márquez and García-Pardo 2010) (Márquez, Pedregal *et al*. 2015). The signal processing is based on system identification techniques in discrete time to estimate potential faults. The Hilbert Transform and Wavelet Transform will be employed to work in conjunction with a peak detection algorithm to determine which echoes come from the edges of the plate, and which echo come from the defect. The attenuation curve is obtained through the highs of the echoes of the edges, and the severity of damage is obtained by comparing the echo that comes from the defect to the curve (Nguyen,

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Ho *et al*. 2013).

The article is organized as follows: The article is organized as follows; Section 2 describes the electromagnetic acoustic transducer; Section 3 explains the procedure to obtain the data. The methods to determine the size of the defect and the employed signal processing are detailed in Section 4; and, finally, the main conclusions are drawn in Section 5.

2. A new electromagnetic acoustic transducer for condition monitoring

The electromagnetic acoustic transducer (EMAT) is a transducer for non-contact sound generation and reception using electromagnetic mechanisms (Fig. 1) (Seshadri, Krishnamurthy *et al*. 2016) (Lee and Sohn 2012). It has been widely used in non-destructive testing in the generation of Shear and Lamb waves (Wang, Yuan *et al*. 2015). A new EMAT has been developed specifically for this purpose, with a specific configuration of coil and magnets.

A 3 mm thickness plate of 316Ti steel is employed in the experiments. The EMAT uses a race track coil with periodic permeant magnets to generate shear waves (SH0 mode) in the plate. The dimension of each EMAT is 15x5x5 mm3. The distance between magnets is 1 mm. In addition, the magnetic strength of each magnet is 0.3 T. The diameter of coil is 0.315 mm, the width 15 mm and length 35 mm, with a lift-off distance 0.1 mm to the sample. The EMAT transducer is shown in Fig. 2.

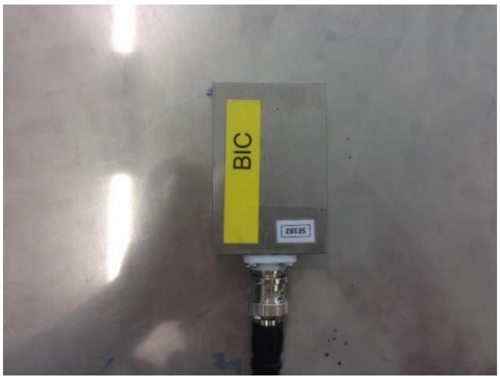


Fig. 1 Electromagnetic Acoustic Transducer

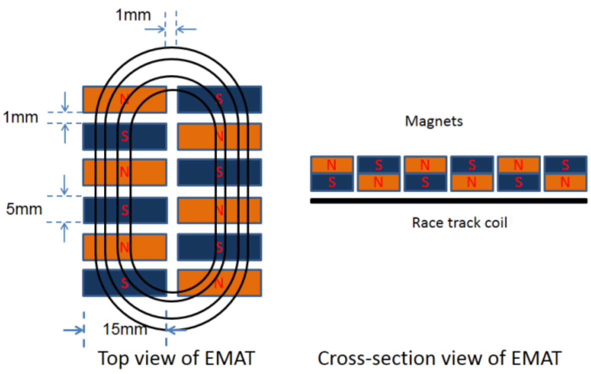


Fig. 2 Configuration of EMAT transducer

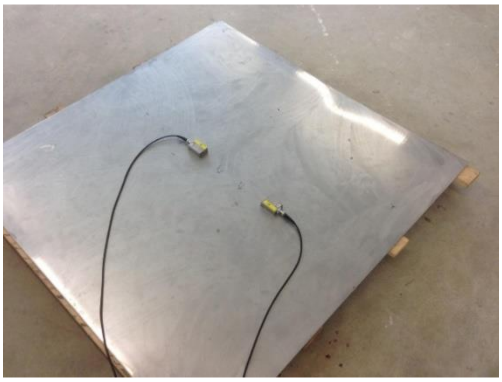
The type of EMAT configuration is mainly to detect transversal defects (spiral cracking, blowout holes, circumferential cracking, bell splitting, etc.). In this case Lorentz forces are generated normal to the plate surface, and therefore the compressive forces produce ultrasound propagating along longitudinal direction through the plate for inspection.

3. Experimental procedure.

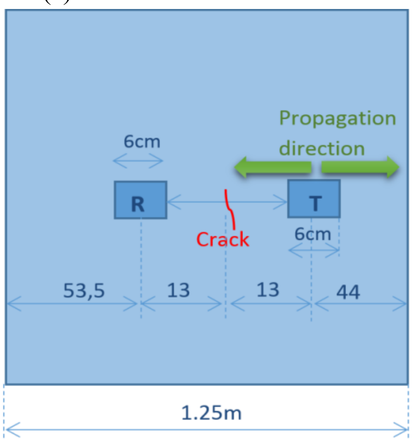
A defect has been induced in a 3 mm stainless steel plate in order to visualize the automatic location of the events. The depth of the cut is 1mm, then the depth was increased to 1.5 mm and 2 mm. Fig. 3 shows the placement of the EMAT and the crack location. EMAT transducer is excited by a 256 kHz and six cycles pulse. Shear waves are generated in both directions.

The EMAT (R) receives echoes from the edges and from the crack. Fig. 4 shows the four first reflections produced by the boundaries.

Shear waves are non-dispersive, i.e., the propagation velocity of these waves is not frequency dependent. The propagation velocity of Shear Waves depends on the material properties (Tweten, Okamoto *et al*. 2015). The propagation velocity for the 3 mm austenitic steel plate (316Ti) is 3020 m/s. This is an advantage to locate events on the plate with high accuracy.



(a) EMAT's on Stainless Steel



(b) EMAT's Arrangement schme

Fig. 3 Actuator and sensor placement on the steel plate

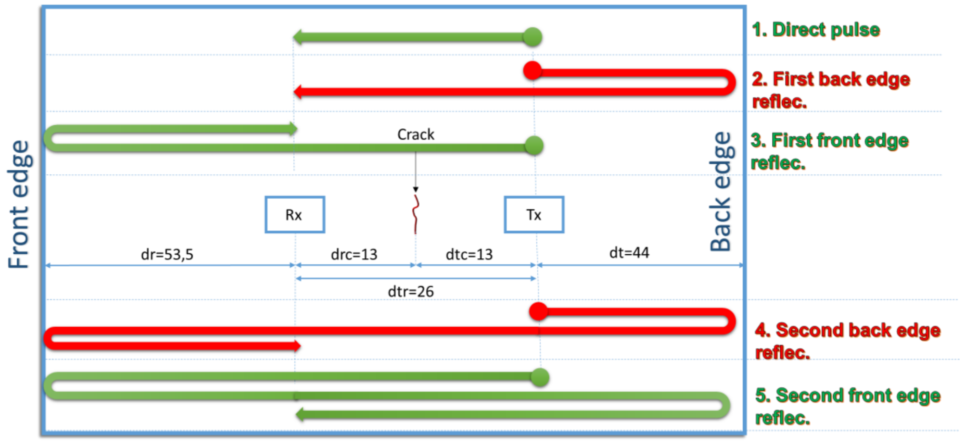


Fig. 4 Reflections from the edges registered by sensor (Rx)

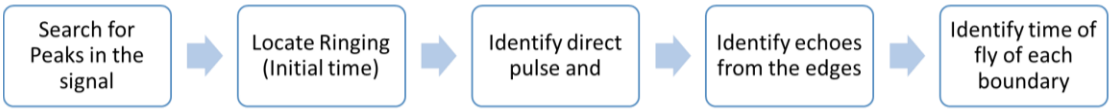


Fig. 5 Algorithm scheme of identification of echoes from edges

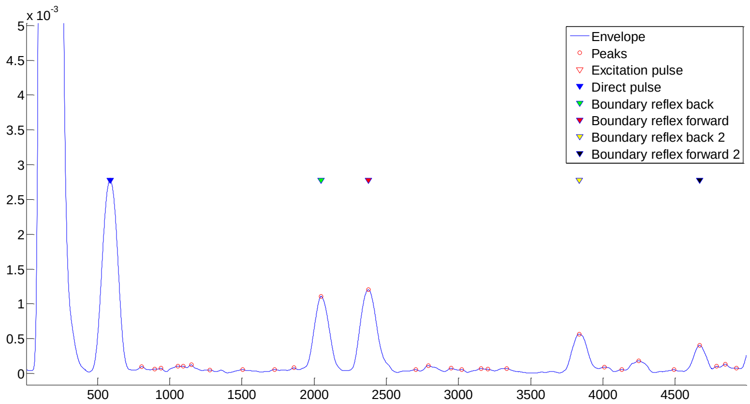


Fig. 6 Direct pulse (1) and edges reflections (2,3,4 and 5)

4. Size damage determination

The approach presented in this paper is based on comparing the energy of an ultrasonic pulse reflected from a crack with the attenuation curve of the pulse. Signal processing is performed in order to highlight important events in the collected signal, like reflected echoes from the edges. The applied signal processing consists of the Wavelet Transform and the Hilbert Transform. Wavelet Transform is used to decompose the signal into multiple levels according to different frequency ranges (Dong, Shi *et al.* 2010). The Wavelet family employed for the signals has been Daubechies with seven levels of decompositions. The fifth detail decomposition "D5" contains more relevant information about the echoes and low signal noise ratio without delay regarding to the original signal.

The amount of energy of each echo can be quantified easily using a Hilbert Transform to generate the signal envelope (Michaels 2008). The Hilbert transform is an approach to study the energy distribution of a Shear wave in the time domain (Chen, Yan *et al.* 2007) (Betz, Staszewski *et al.* 2006). It is necessary to smooth the envelope in order to avoid detecting false peaks in the signal, which usually is associated with an event.

The approach presented in this paper identifies the events within the signals that are obtained from elements as boundaries or welds. The process shown in Fig. 5 consists of the following steps:

- Peak searching: It is important to select the proper threshold for this purpose.
- Identify the first event that indicates the instant when the actuator is excited.

- Identify the first pulse received by the sensors of each wave mode (direct pulses).
- Identify echoes from the edges: The experimental Time of Flight (ToF) of each echo in the signal is obtained and compared with the theoretical ToF that they should have (Kadziński, Tervonen *et al*. 2015).
- The ToF of each echo is identified to calculate the distances travelled.

The numbers 1 through 5 in Fig. 6 indicates the following:

0. The instant when the actuator is excited and emits the pulse.
1. The direct pulse, that is, the shorter distance between the actuator and the sensor.
2. The first reflection from the back edge.
3. The first reflection from the front edge.
4. The second reflection from the back edge.
5. The second reflection from the front edge.

4.1 Obtaining the attenuation curve

Attenuation is generally proportional to the square of sound frequency. There are two main attenuation mechanism: dispersion and absorption. Shear waves, are not dispersive. Absorption is produced by conversion of mechanical energy in heat energy. Acoustic attenuation coefficient represent the amount of sonic attenuation per unit of length.

To determine the magnitude of the defect, it has been employed an approach that identify three echoes which come from the forward path. Attenuation often serves as a measurement tool that leads to the conclusion of the existence of a phenomenon that decreases the ultrasonic intensity.

The two procedures to set the curve are obtained by function of the number of detected echoes that have travelled along the same path.

Two echoes that have travelled along the same path.

In the case in which only two points of the curve are known, for example the amplitude of the direct pulse and the first forward reflection, the behavior of the amplitude decreasing can be expressed as

$$P = P_0 e^{-\alpha d} \tag{1}$$

Where $P0$ is the amplitude of the signal in the direct pulse, P is the reduced amplitude after the wave has travelled a distance d (first reflection), and e is the Napier's constant. The quantity α is the attenuation coefficient of the wave whose dimension are nepers/length.

Attenuation can be determined by evaluating the multiple backwall reflections seen in the signal (Fig. 7).

The attenuation coefficient of the signal can be obtained as

$$\alpha(Np/m) = -\frac{\ln\left(\frac{P}{P_0}\right)}{d} \tag{2}$$

The logarithmic unit Decibels is more common unit used to relating the amplitudes of two signals

$$\alpha(dB/m) = -\frac{\ln\left(\frac{P}{P_0}\right)}{0.1151 * d} \tag{3}$$

Eqs. (1)-(3) have been used to obtain the attenuation curve of this path (Williams, Michaels *et al*. 2016). When the crack is deeper, the echo coming from it has a higher amplitude. To assign an importance measure to the crack, the peak of the echo that comes from the crack is compared with the attenuation curve in this location. Since a total cut behaves similarly to an edge, the attenuation curve serves to provide a relevance percentage of each defect.

Three echoes that have travelled along the same path.

In the case in which three points of the curve are known, an attenuation curve can be generated more accurately. The *Levenberg-Marquardt* algorithm is employed for generating the attenuation curve. This method, also called the Damped least-squares method, generate the attenuation curve using three known points of the curve, which is the direct pulse, the first and the second edge reflection, all the way forward.

The *Levenberg-Marquardt* algorithm is an iterative technique that locates the minimum of a function that is expressed as the sum of squares of nonlinear functions. It has become a standard technique for non-linear least-squares problems.

The *Levenberg-Marquardt* algorithm is an iterative procedure (Marquardt 1963). An initial parameter β is used to start the iteration and, in each iteration step, the parameter β is replaced by a new estimate $\beta + \delta$. The new functions $f(x_{i,}\beta + \delta)$ are approximated by their linearization. The Eq. (4) defines the curve

$$S(\beta) = \sum_{i=1}^{m} \left[y_i - f(x_{i,}\beta)\right]^2 \tag{4}$$

Where $S(\beta)$ is the sum of the squared errors of the function to be minimized, x_i and y_i are the location and amplitude of each point respectively, $f(x_{i,}\beta)$ is the image of the points x_i and y_i through the fitted curve and β is the fitting parameter of the curve.

The attenuation curve, see Fig. 8, drawn for this method shows the behavior of the ultrasonic pulse traveling the forward way.

4.2 Obtaining the attenuation curve of the reflected pulse

In order to determine the relevance percentage of the defect, it is necessary to obtain two attenuation curves. The attenuation curve belonging to the pulse emitted directly by the transducer, and the attenuation curve belongs to the portion of the pulse that has been reflected due to the defect.

The identification of the echo from the crack (Fig. 9) provides the time when it is registered by the sensor. t_{echo} is the time when the echo reflected by the crack is collected by the sensor, being h_{echo} the height of the echo. Once the t_{echo} is identified, it will be determined the time when the echo was reflected by the crack, t_{crack}.

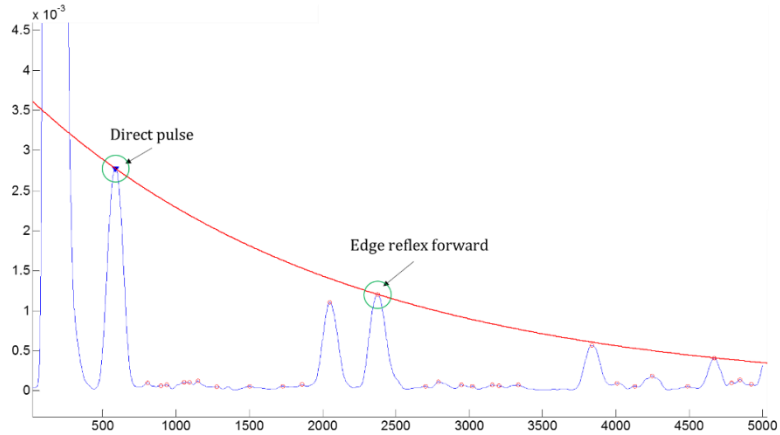


Fig. 7 Attenuation curve of the forward path using two points

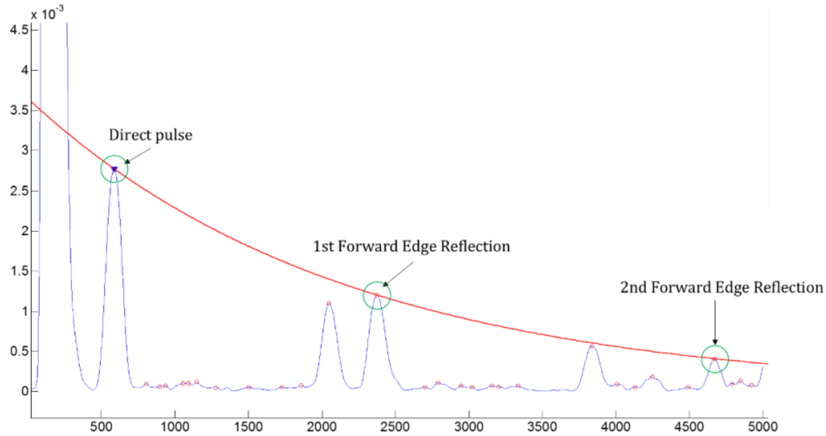


Fig. 8 Attenuation curve of the forward path using Levenberg-Marquardt method

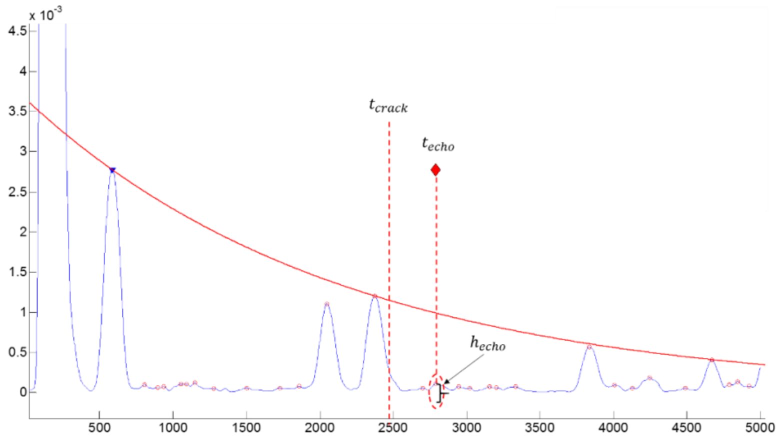


Fig. 9 Time when the pulse is reflected from the crack and time when the echo is collected for the transducer

Knowing the distance between the crack and the sensor ($d_{crack\text{-}sensor}$), t_{crack} can be determined as

$$t_{crack} = t_{echo} - \frac{2 \cdot d_{crack-sensor}}{v} \qquad (5)$$

where v is the propagation velocity of the ultrasonic pulse. In t_{crac},_right at that moment, part of the energy of the ultrasonic wave through the defect and other portion of the energy is reflected. The echo has a smaller amplitude and it is necessary to adapt its attenuation curve (Fig. 10). Echo height is sought in the attenuation cure obtained previously.

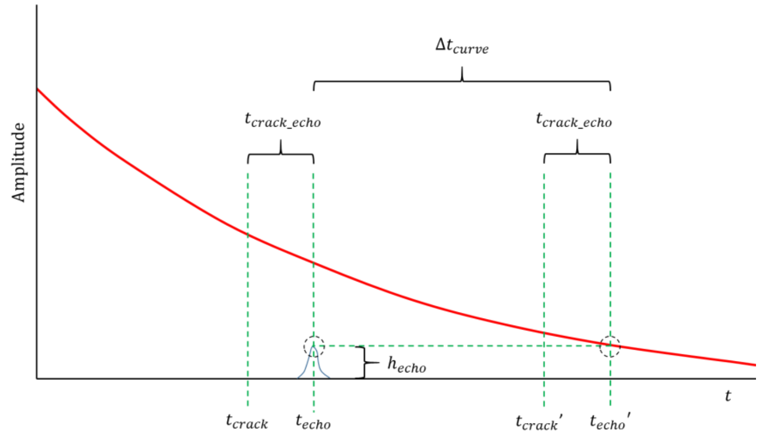


Fig. 10 Displacement of the attenuation curve to adapt the behavior of the ultrasonic pulse

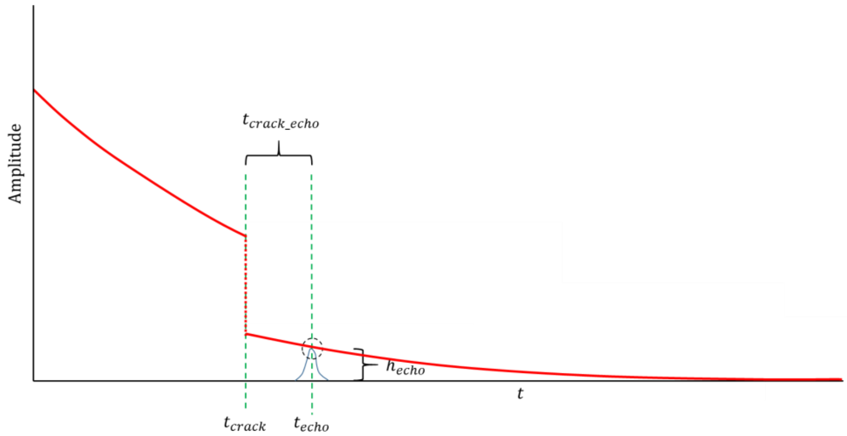


Fig. 11 Attenuation curve of an ultrasonic pulse that is reflected from a defect

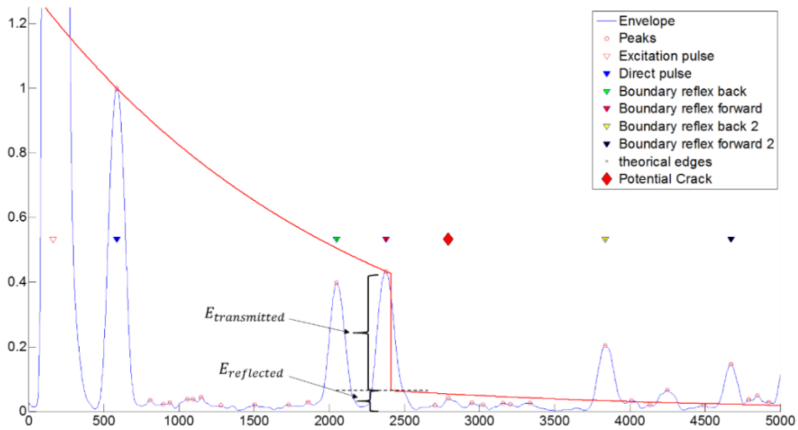


Fig. 12 Energy of an ultrasonic pulse before and after being reflected by a defect

The instant t_{echo}' in which the attenuation curve has a height equal to the echo of the defect is defined as

$$t_{echo}' = \frac{\ln\left(\frac{P_0}{h_{echo}}\right)}{v \cdot \alpha} \qquad (6)$$

The echo attenuation curve is shifted to the instant when the pulse is crossing the crack. The curve after t_{crack}' is shifted until the instant t_{crack}. The displacement of the curve is given by

$$\Delta t_{curve} = t_{echo}' - t_{echo} \qquad (7)$$

Finally the curve representing the behavior of the ultrasonic pulse before and after of the crack reflection is shown in Fig. 11.

Table 1 Depths and relevance degree of each cut

Cut Depth	Relevance degree
1.00 mm	18.68 %
1.50 mm	21.70 %
2.00 mm	25.05 %

It can be expressed as

$$P = \begin{cases} P_0 \cdot e^{-\alpha \cdot v \cdot t}, & 0 \leq t < t_{crack} \\ P_0 \cdot e^{-\alpha \cdot v \cdot (t + \Delta t_{curve})}, & t_{crack} \leq t < \infty \end{cases} \quad (8)$$

4.3 Determining the severity of the damage

The degree of importance is analysed as a function of the position and height of the reflected echo from the defect. The attenuation curve establishes the amplitude of the echo along a distance and serves as a reference to compare the energy of a reflected echo.

Fig. 12 shows the portion of energy of an ultrasonic pulse that is transmitted when it cross a defect, and the energy that is reflected from the defect.

The importance of the defect can be established relating the energy is transmitted to the energy that is reflected. This method allows to obtain an approximate percentage of the severity of the default, but there are other factors that can affect the results, such as the direction of the crack. The percentage of the severity of the damage can be expressed as

$$Relevance\ degree = \frac{E_{reflected}}{E_{reflected} + E_{transmitted}} \quad (9)$$

where $E_{reflected}$ is the reflected energy from the crack, $E_{transmitted}$ is the transmitted energy that cross the default and the $Relevance\ degree$ is the estimated percentage of the severity of the damage.

There have been several tests on the steel plate where cuts have been made with different depths. The results are shown in Table 1.

5. Conclusions

The development of a new electromagnetic acoustic transducer for condition monitoring together with the use of advanced signal processing approaches, provide more precise information about the structural state of the system, which leads to increase the reliability, availability, safety and investing returns. This work presents a new approach based on signal processing to automatically identify, locate and determine the severity of a defect in a plate. Similarly, it could be used to detect defects and welding in pipes. Particularly, this approach comprises a pre-filter and denoising using Wavelet methodologies and the Hilbert Transform to detect relevant peaks. Time of Flight of the echoes are calculated theoretically and then compared with the experimental times to determining which echoes come from the edges. Any other echo represents a potential crack. Echoes from the same defect traveling different paths are compared and the defect is located considering each amplitude. Finally, the attenuation curve of the ultrasonic echoes is determined to provide a estimation of the defect severity.

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