Ultrasonic Pulse-Echoes and Eddy Current Testing for Detection, Recognition and Characterisation of Flaws Detected in Metallic Plates

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Abstract. In order to improve manufacturing quality and ensure public safety, components and structures are commonly inspected for early detection of defects or faults which may reduce their structural integrity. Non Destructive Testing (NDT) and Evaluation (NDE) techniques present the advantages of leaving the specimens undamaged after the inspection. NDT involves treating defect detection and characterization as inverse problems. In experimental NDT/NDE, the available measurement data are exploited in order to some clues may emerge in the inspection signal that are possibly representative of structural modification of the specimen, like cracks, delaminations and porosities. In this paper, a comparison of Ultrasonic Pulse-Echoes and Eddy Current Testing techniques is presented to investigate critical flaw-structure configuration, such as porosity in metallic plates. The proposed procedure exploits a fuzzy classifier that receives a set of extracted features worth of inputs by means of Wavelet Transform. The output of the system is a sort of codification related to each kind of damage (so-called class). In order to refine the procedure, Shannon Fuzzy Entropy has been taken into account.

1. Introduction to the Problem

Most industrial applications require that the manufacturing quality of pieces must be certified, thus components and structures should pass inspection tests in order to avoid the presence of defects that can reduce their life cycle and/or efficiency. NDT is particularly relevant to the inspection of large and expensive components [1]. The main purpose of a NDE technique is to provide information about the presence/absence, location and size of cracks potentially present on the inspected specimen. In this paper, metallic plates have been inspected in order to detect a particular kind of defect, i.e. porosities. They are spherical/elliptical micro-voids, distributed within the volume of plate and caused by errors in manufacturing, generally induced by incorrect pressure and temperature gradients during the extrusion phase. Dealing with porosities is generally very difficult, as by using Eddy Current Tests (ECTs) as by using Ultrasonic Tests (UTs). In fact, porosity is typical of thick plates, while ECTs are usually used in order to analyze superficial or sub-superficial flaws. Moreover, position and direction of extension of porosities can make useless an eddy current inspection. On the other hand, volumes with few small pores (tens or also hundreds of microns) could be not detected by pulse-echo techniques, even if UTs guarantee a bigger depth of analysis. When the defected volume contains a sufficient number of (and/or enough large) pores, these scatter the signal, so that there are not well defined flaw peaks, but a number of puzzling overlapped indications. In favourable cases, various small peaks are usually produced, generally having an amplitude lower than 25% of the front echo (they can be masked by the noise). Depending on the density of the pores, the back-wall echo amplitude could be greatly reduced (severe porosity), confirming the presence of a diffused anomaly. In correspondence of a node-like configuration (Fig. 1) the situation can be more complicated, the back-wall echo being absent in any case. So that only severe porosity (with amplitude approximately higher than 50% of the front echo) can be revealed.

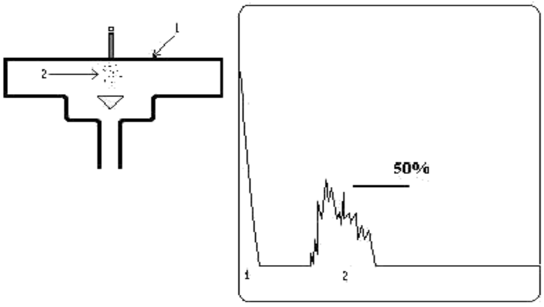

Fig. 1. Porosity defect having a node-like configuration and its response under UT analysis.

In this paper, UTs have been carried out in order to characterize the depth of porosity starting from time-domain ultrasonic signals (A-scans). In order to solve the inverse problem, a Fuzzy Inference System (FIS) has been introduced obtaining banks of IF…THEN fuzzy rules, in virtue of which the system under investigation behaves as a linguistic structure. In particular, minimization of Shannon Fuzzy Entropy (SFE) has been considered to refine the procedure, obtaining a FIS with minimal number of rules useful to manage defects without any loss of information [2]. A Wavelet pre-processing extracted features related to the local trend of the signal [2] in order to avoid the "curse of dimensionality" [3], and numerical simulations exploiting Finite Element Method (FEM) have been carried out to build the database used to implement FIS. It has been subsequently tested on experimental measurements, and obtained results have been compared to simulations carried out by using ECTs and the same fuzzy-based procedure, in order to validate the proposed heuristic process of inversion and to consider the reliability of UTs in detection of deep flaws. Wavelet pre-processing as well as FIS implementation and test have been carried out in Matlab© workspace. The paper is organized as follows: Section 2 describes the used NDT/NDE techniques and characteristics of the implemented database; Section 3 describes the procedure exploited to implement and train FIS; Section 4 describes retrieved results and, finally, some conclusions are depicted in Section 5.

2. UTs and ECTs: Theoretical Overview and Numerical Simulations

In order to improve manufacturing quality and ensure public safety, components and structures are inspected for defects or faults which may reduce their structural integrity. Among the methods of testing developed for maintenance and inspection purposes, non-destructive testing and evaluation (NDT/NDE) techniques present the advantages of leaving the specimens undamaged after inspection [4].

2.1 Eddy Current Testing

The eddy current method exploits the principle of electromagnetic induction to inspect a conducting material [4]. An alternating current of fixed frequency generated by an exciting coil creates a magnetic field in the vicinity of the coil. The alternating magnetic field is perpendicular to the direction of the current and parallel to the axis of the coil. The coil is held in a probe which is scanned over the surface of the specimen. If the coil is brought in the vicinity of a conductive material, the exciting magnetic field of the coil induces electrical eddy currents in the material. These currents give rise to a secondary magnetic field in the specimen called the induced magnetic field. This field is affected by the presence of a flaw on the specimen, and therefore, the eddy currents are also perturbed by this surface discontinuity. If it is possible to measure the magnitude and the phase of the coil electrical impedance, the variation of the eddy current distribution on the surface can be carried out. The strength of the induced currents falls off exponentially as one moves along the central axis of the inducing field away from the source, to a greater or lesser degree depending on the driver frequency, conductivity of the material, and relative permeability. As a general rule, high driving frequency or high conductivity implies a smaller depth of penetration. In fact, 63% of the induced current is enclosed between a depth δ and the material surface, where δ is given by [4]:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \tag{1}$$

where ω is the driving angular frequency, ρ is the material's resistivity, and μ is the absolute permeability of conductor. Impedance of exciting coil can be significantly conditioned by a conductor having a 2δ -3δ thickness [5].

2.2 Ultrasonic Testing

Ultrasonic waves are caused by mechanical vibrations that occur because of the elastic properties of the material [4]. These waves are induced by the vibration of particles in the material. Ultrasonic waves can be generated using a number of methods, but in most non-destructive testing applications, piezoelectric transducers are used as both transmitter and receiver probes. A piezoelectric material has the property to produce electric charges on the surface when it is deformed by external pressure. If the pressure is reversed, the polarity of electric charges is reversed. If a piezoelectric material is placed between two electrodes and an electric field is applied, the material changes shape. This is called an inverse piezoelectric effect. While utilizing the effect, alternating electric current can be applied to the piezoelectric plate and generate mechanical oscillation. There are many varieties of materials that display piezoelectric properties: natural crystals, such as quartz and lithium sulphate, and fabricated polycrystalline ceramics, such as barium titanate, can be used as piezoelectric materials. The ultrasonic wave is generated by applying an electrical pulse to the transmitter probe. The probe produces a short ultrasonic pulse that is propagated into the specimen through a coupling medium. The reflected portion of the ultrasonic wave returning to the transducer results in a small alternating voltage that is then fed to the amplifier. This amplified signal provides both time of flight information as well as indication of the strength of the echo from discontinuities in the path of the ultrasonic wave. Velocity of longitudinal waves is given by:

$$VL = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \tag{2}$$

where E is the elastic Young's modulus, ρ is the material's density and σ is the Poisson's ratio. It is necessary to eliminate any air intrusion between probe and material surfaces in order to obtain a good coupling between ultrasonic sensor and analyzed specimen. Coupling material must be water-resistant and ultrasonic-transparent; moreover, it does not have to damage specimen surface. The coupling medium can be selected as: SAE 30 oil, gel for ultrasonic test, water, glycerine. It is very important to use the same medium as in calibration as in operative phases. Normally, it is possible to observe echoes from the specimen's surface, the bottom surface, and eventually present flaw. The ultrasonic signal can be rectified and a peak detection operation performed to obtain a single maximum in each pulse. The problem in the ultrasonic measurements consists of the sensibility of the sensor to the specimen roughness, that means a low signal-to-noise ratio; nevertheless, the measurement resolution is very high, in fact clean variations in the measured signal occurs just in the location where the defect is present. Problems can occur when the defect is too thin if compared with the spatial resolution used during the scanning of the sensor over the inspected plate.

2.3 Database Implementation: FEM-based Numerical Simulations

As described in the Introduction, detection and characterization of porosity in metallic plates is not an easily solvable problem. Characteristics of specimens, misplacement of sensors, skewing effects between apparatus of automatic motion and the same sensors are hard drawbacks. Aim of our research is contributing to solution of the following inverse problem: characterizing the depth of porosity starting from the A-scans, by using a fuzzy approach. It is able to ”learn” complicated, non-linear and multivariable relations from the experience; therefore, it is important to implement a suitable database, subsequently useful to train the FIS. Considering a steel-made specimen having a thickness of 10cm, 450 FEM simulations of UTs have been carried out [6], varying depth and extension of porosity, operative frequency and dimension of probe (Table 1). Subsequently, each ultrasonic signal has been pre-processed by Wavelet Transform [7], considering only the approximation coefficients (input patterns) as useful information. Each pattern has been linked to the correspondent codify of porosity’s depth (FIS output, see Table 2); in a similar way, 450 FEM-based ECTs have been carried out. An additional input flag has been added to distinguish ultrasonic from eddy current signals; retrieved database (DBTrain) has been subsequently used in order to train the FIS.

Table 1. Range of variation for UT-related quantities used in FEM numerical simulations

Depth of porosity (cm)	Extension of porosity (mm)	Frequency of ultrasonic probe (Hz)	Dimension of diameter of ultrasonic probe (mm)
[0.2÷9.5]	[0.2÷0.8]	[350÷4000]	[2÷8]

Table 2. Considered range and correspondent codification of porosity’s depth

Range of depth	[5%÷15%]	[15%÷30%]	[30%÷50%]	[50%÷70%]	[70%÷90%]
Codification	0	100	200	300	400

3. A Minimal Fuzzy Entropy Model for Characterization of Porosity’s Depth

DBTrain has been used to build a thematic map starting from a Fuzzy model by using Fuzzy Entropy Theory [8]. In particular, a Fuzzy Entropy measure based on SFE has been considered, and a mathematical model able to build a pattern classifier with minimal entropy has been implemented. This is the proposed Minimal Fuzzy Entropy (MFE) classifier. In this way, it is possible to implement a classifier which can be able to distinguish depth of presence of a porosity, even if it is so diffused to cancel the echo of bottom.

3.1 MFE: Decisional Models Implementation and Classification Approach

In a pattern classification problem, u_{jk} is the level of fuzzy membership of j^{th} defect to k^{th} class (k=1,2,…,N). Let N classes are given, the shading-type partition produces N informative layers representing membership levels of the defects to the selected classes. Shannon index has been widely applied to evaluate the fuzziness degree of a fuzzy classification. Entropy of a defect, H, i.e. its amount of statistic information, is:

$$H = -\sum_{k=1}^{N} u_{jk} \ln u_{jk} \tag{3}$$

where $\ln(u_{jk})=0$ when $u_{jk}=0$ [8]. According to fuzzification of Shannon Entropy principle, a new SFE-based approach has been considered through construction of a Minimal Fuzzy Entropy Decisional Model (MFEDM) for each considered feature. In order to build each MFEDM, the following algorithm has been considered:

1. let us denote $\mathbf{X} = \{x_1, \ldots, x_n\}$ as a universal set of pattern space elements;
2. let Ã be a k-elements fuzzy set (k<n) defined on an interval of pattern space; membership degree mapping of x_i elements into the fuzzy set Ã is denoted as $\mu_{\tilde{A}}(x_i)$;
3. let $C_1, C_2, \ldots, C_m$ be the m classes into which the n elements are divided;
4. let $S_{Cj}(x_n)$ represent a set of elements of j^{th} class into the universal set X;
5. let us define D_j (4), the match degree with the fuzzy set Ã for elements of j^{th} class in an interval, where j=1, 2, …, m:

$$D_j = \frac{\sum_{x \in S_{Cj}(x_n)} \mu_{\tilde{A}}(x)}{\sum_{x \in X} \mu_{\tilde{A}}(x)} \tag{4}$$

6. let us define SFE of elements of jth class in an interval, $SFE_{Cj}(\tilde{A})$:

$$SFE_{C_j}\left(\tilde{A}\right) = -D_j \log_2 D_j \tag{5}$$

7. let us define SFE in a universal set **X** for elements in an interval, $SFE(\tilde{A})$:

$$SFE\left(\tilde{A}\right) = \sum_{j=1}^{m} SFE_{C_j}\left(\tilde{A}\right) \tag{6}$$

In (6) $SFE_{Cj}(\tilde{A})$ is a non-probabilistic entropy. Therefore, the term match degree for D_j has been coined. In the next section, the case study is going to be explained.

3.1 Applicative Algorithm of MFE Model

In order to explain the applicative algorithm of previously proposed MFE mathematical model, let us consider an l-dimensional pattern $p \in \mathbf{X}$, $p = (p_1, p_2, \ldots, p_l)$ (train pattern), which is composed by l features (inputs) and belongs to class C_j, $1 \leq j \leq m$. A Fuzzy System is obtained from DBTrain by subtractive clustering, with a user-defined number of fuzzy membership functions (FMFs) for each input (n_{fmf}). Considering the r^{th} input ($1 \leq r \leq l$) of each train pattern p_t, let us define a number of intervals equal to ($n_{fmf}+1$); interval boundaries are defined as follows: left-most interval boundaries are [min(p_t,r,) c_1]; boundaries of each s^{th} internal interval are [c_s-1, c_s+1]; right-most interval boundaries are [cnfmf-1, max(pt,r)]. For each s^{th} interval, $SFE(\tilde{A}_s)$ is calculated according to (4)-(6); thus SFE of considered r^{th} input (SFE_r) is the summation of all $SFE(\tilde{A}_s)$, s=1,…,(n_{fmf}+1). It is the total amount SFE_{tot} of SFE. When SFE_{tot} has a minimum, the procedure is stopped and the relative FIS is stored.

4. Experimental Evaluation of MFE

Reliability of implemented MFE has been tested by means of experimental measurements carried out at Non Destructive Testing Lab, DIMET Department, University “Mediterranea” of Reggio Calabria by using Ecograph 1086© of Karl Deutsche® farm. Five steel plates having with a thickness equal to 10 cm have been used, with porosities belonging to the five different classes. In this way, 40 different tests have been carried out by using 2 different probes (having a range of operative frequency of [1÷4] and [8÷10] MHz respectively). Sensor having higher operative frequency has been used to detect sub-superficial porosity; both of probes have a diameter of 4.2 mm. In order to obtain well-defined echoes, amplification gain of ultrasonic wave has been tuned into a range of [0÷120] dB. It has been possible to interface the Ecograph 1086© with a PC by means of RS232 port and ECOM85© software. In this way, it has been possible to export each signal in ASCII format for subsequent elaborations in Matlab©. Here, each experimental signal has been pre-processed by using Wavelet Transform and retrieved wavelet approximation coefficients have been used to implement a testing database (DBTest). Depth of porosity has been correctly detected for 36 experimentations (90% of reliability, see Fig. 3). It is possible to denote how 75% of misclassified porosities are located between 50% and 90% of deepness, with a 30% of performance decrement in deep-porosity classification (Fig. 4 shows the error trend as a function of plate thickness).

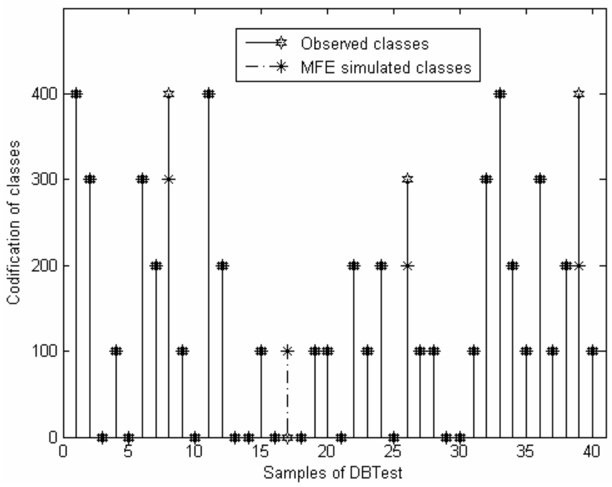

Fig. 2. Graphical plot of MFE performances: hexagrams are observed classes, stars are MFE simulations

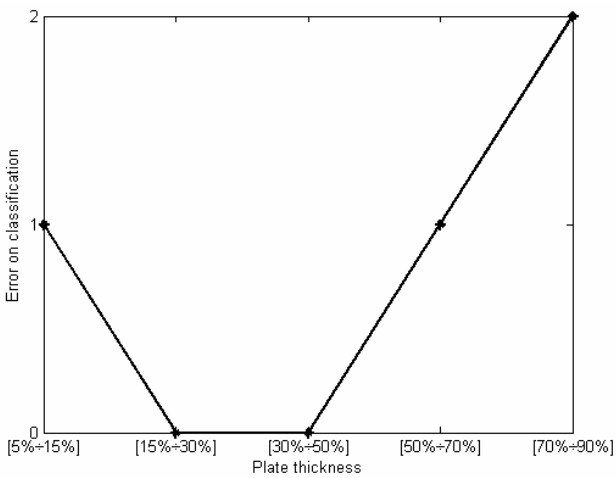

Fig. 3. Trend of classification error vs plate thickness.

4.1 Validation of MFE approach by using ECTs

In order to validate results obtained by UTs, the same five steel-made specimens have been subjected to eddy current inspection at our laboratory. In this case, the applied sensor was a FLUXSET®-type probe [9], moved over each specimen by means of a 0.5 mm-step automatic scanning procedure along x and y axes (Fig. 4).

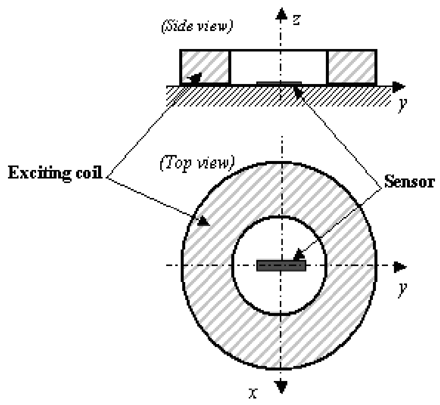

Fig. 4. Schematic draw of the probe.

A driving signal - triangular shape, 125 kHz frequency, 2Vpp amplitude - was applied to saturate the core material inside the probe, and different exciting fields have been generated close to the specimens, thus inducing eddy currents on the surface as well as on subsurface layers. Because of limitations to the eddy current phenomenon, it has been possible to validate MFE only for porosity located into the range [5%÷30%] of deepness. Retrieved results confirm the classification obtained by UTs.

5. Conclusions

In this paper an heuristic approach to locate position of porosity into the volume of metallic plates has been described. It is based on Fuzzy Inference exploiting the criterion of Shannon Fuzzy Entropy minimization, using a Wavelet pre-processing to extract the most significant features related to local trends of the ultrasonic signals. In classification phase, a self-implemented MFE system has been used in order to determine the defect's depth and quickly classify results with low-computational complexity algorithms. A classification has been carried out on five depth's ranges ([5%÷15%], [15%÷30%], [30%÷50%], [50%÷70%] and [70%÷90%]) calculated on the considered plate thickness (10cm). Numerical FEM-based simulations of UTs and ECTs have been taken into account in order to build a suitable training database, useful to train the MFE. Subsequently, experimental measurements have been carried out at our Non-Destructive Testing laboratory by using a typical commercial equipment for UTs, in order to evaluate the performances of implemented MFE. Finally, a certain number of ECTs have been considered in order to validate the results retrieved by using UTs, if possible.

Implemented MFE performances are very encouraging, above all taking into account the problems related to porosity detection and localization in UTs. Moreover, the noticeable thickness of considered steel plates can lead to a very difficult inspection; working with proposed MFE approach can overcome some of these inconveniences, with a real-time application able to detect porosity even at remarkable deepness. Considering the 40 patterns of DBTest, in fact, only an error has been obtained into the depth's range [5%÷50%] (24 tests). Error incidence increases with deepness, with 3 misclassification into the range [50%÷95%] of deepness. Nevertheless, two of these misclassified porosities are considered as deep flaws, and only a pattern belonging to the depth's range [70%÷90%] is located in the middle of plate thickness. Experiments with eddy current validate the optimal classification abilities of MFE for superficial and sub-superficial flaws. Unfortunately, it was not possible to inspect deep region of plate by means of ECTs, so confirming its physical restriction in non-destructive approaches. Table 1 resumes retrieved results of classification

Table 1. MFE classification results: the 40 patterns of DBTest are grouped by related class and a relative error percentage for each class is calculated

Depth's range	Number of observed patterns	Number of pattern classified by MFE	Relative error percentage	Details on errors
[5%÷15%]	12	11	-8.33%	Missing pattern has been assigned to [15%÷30%]
[15%÷30%]	12	13	+8.33%	A pattern comes from [5%÷15%]
[30%÷50%]	6	8	+33.33%	A pattern comes from [50%÷70%], another from [70%÷90%]
[50%÷70%]	5	5	0%	A pattern is assigned to [30%÷50%]; a pattern comes from [70%÷90%]
[70%÷90%]	5	3	-33.33%	A pattern is assigned to [30%÷50%], another to [50%÷70%]

In conclusion, SFE-based proposed approach is useful to classify hardly-detectable porosities. It should be a suitable method to implement specific classifiers able to overcome limitations which are intrinsic to inspection techniques, so giving a valid support to technicians in real-time industrial applications.

References

[1] Libby H.L., *Introduction to Electromagnetic Nondestructive Test Methods*, Wiley-Interscience, New York, 1971.

[2] Barrile V., Cacciola M., Versaci M., "Fuzzy Classification with Minimal Entropy Models to Solve Pattern Recognition Problems: a Compared Evaluation in SAR Imagery", *WSEAS Transactions on Information Science and Applications*, Vol. 3, Issue 4, 2006, pp. 860-867.

[3] Bellman R.E., *Adaptive Control Processes*, Princeton University Press, Princeton, NJ, USA, 1961.

[4] Bray D. E., McBride D., *Nondestructive Testing Techniques*, Wiley-Interscience, New York, USA, 1992.

[5] Blitz J., *Electrical and Magnetic Methods of Non-destructive Testing, Second Edition*, Chapman & Hall, London, UK, 1997.

[6] Biro O., Preis K., Ticar I., "A FEM method for eddy current analysis in laminated media", *COMPEL*: *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, Vol. 24, No. 1, 2005, pp. 24-248.

[7] A. Graps, An Introduction to Wavelets, IEEE *Comp. Science & Engineering*, 2-Issue 2 (1995), 50-61.

[8] Kosko B., *Fuzzy Engineering*, Prentice Hall International Editions, Upper Saddle River, USA, 1997.

[9] A. Gasparics, C.S. Daroczi, G. Vertesy, J. Pavo, Improvement of ECT probes based on Fluxset-type magnetic field sensor, *Electromagnetic Nondestructive Evaluation*, IOS Press, No. 2, 1998, pp. 146-151.

[10] Morabito F.C., Simone G., "NDT image fusion using eddy current and ultrasonic data", *COMPEL*: *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, Vol. 20, No. 3, 2001, pp. 857-868.