Combining fuzzy logic and neural networks in classification of weld defects using ultrasonic time-of-flight diffraction

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The ultrasonic Time-of-Flight Diffraction (TOFD) technique is gaining rapid prominence in non-destructive testing due its high accuracy in detection, positioning and sizing of weld flaws in steel structures. Until lately, TOFD was used reliably only in fast-track inspections due its portability in automatic scanning and data acquisition. However, data processing and interpretation of TOFD data requires expert knowledge and accuracy largely depends on the operator experience. Hence, results suffer errors as interpretation is often carried out offline, especially when dealing with large volumes of data. A fully comprehensive automatic detection and interpretation can be achieved using advanced image and signal processing and artificial intelligence techniques, thus reducing time, cost and errors in the detection, interpretation and classification of flaws in steel structures.

This paper presents current research using advanced methods for automatic interpretation and classification of weld defects in TOFD data. In the classification stage three different classification techniques are employed and compared: an artificial neural network-based classifier, a fuzzy logic-based classifier and a hybrid neural-fuzzy classifier. A neural classifier can learn from data, but the output does not lend itself naturally to interpretation. A fuzzy classifier on the other hand consists of interpretable linguistic rules, but they cannot learn. A neural-fuzzy classifier is based on a three-layer feed-forward neural network and combines the merits of both neural and fuzzy classifiers while overcoming their drawbacks and limitations. The developed neural-fuzzy classifier exhibits high levels of accuracy, consistency and reliability, with acceptably low computational time and is a promising new development in the field of semi-automatic weld inspection.

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1. Introduction

Ultrasonic TOFD is good at detecting most internal defects, results are available immediately, testing can be performed 'on site' – equipment is fully portable, running costs and safety hazards are low. However, TOFD requires experienced operator skills for the interpretation and detection of defects. These days, with advanced technology, ultrasonic testing can be made more accurate, reliable and feasible in most inspection systems[2-7].

Although the data acquisition configuration lends itself conveniently to automation, and methods such as robotic scanning and computer-conditioned data acquisition are routinely used, the crucial processes of data processing and interpretation are still performed off-line manually depending heavily on the skills, experience, alertness and consistency of the trained operator. Results typically suffer from inconsistency and errors, particularly when dealing with large volumes of data. In the light of industrial pressure, the recent trend has been to automate the TOFD data interpretation process in software by adding an element of robustness, accuracy and consistency. This can be achieved by advanced image processing and artificial intelligence techniques to discriminate between subtle variations in visual properties of the data, reducing the overall interpretation time, effort and cost.

The TOFD image provides important characteristics and patterns in recognition of defect types. However, lack of unique visual defect signature interpretation of volumetric flaws is not trivial. Further, TOFD standards and acceptance criteria introduce their own complexities. The prescribed[1] defect classes are planar flaws, volumetric flaws, thread like flaws and point flaws. In this research, statistical image processing methods and algorithms have given excellent results. In the classification stage three different classifiers are used to demonstrate performance of different methods: neural classifier, fuzzy classifier and neural-fuzzy classifier. The TOFD automatic inspection system can be semi or fully automated[3-4][8-9] for the flaw detection in the metal structures.

2. The ultrasonic time-of-flight diffraction technique

TOFD was first described by Silk[6] in detection, sizing and location of defects. The basic TOFD system is a two-probe arrangement consisting of a separate ultrasonic transmitter and receiver as shown in Figure 1.

After propagation of the compressional wave from the transmitter, the first signal to arrive at the receiver is a lateral wave through upper surface. In the absence of defects the second signal to arrive at the receiver is the back-wall echo. The diffracted signal generated at the upper tip of a defect will arrive before the signal generated at the lower tip of the defect. With a time of flight of each flight path, the ultrasonic velocity and the spatial relationships of the two probes known, location and height of defects can be very accurately calculated. The widespread acceptance of TOFD is also

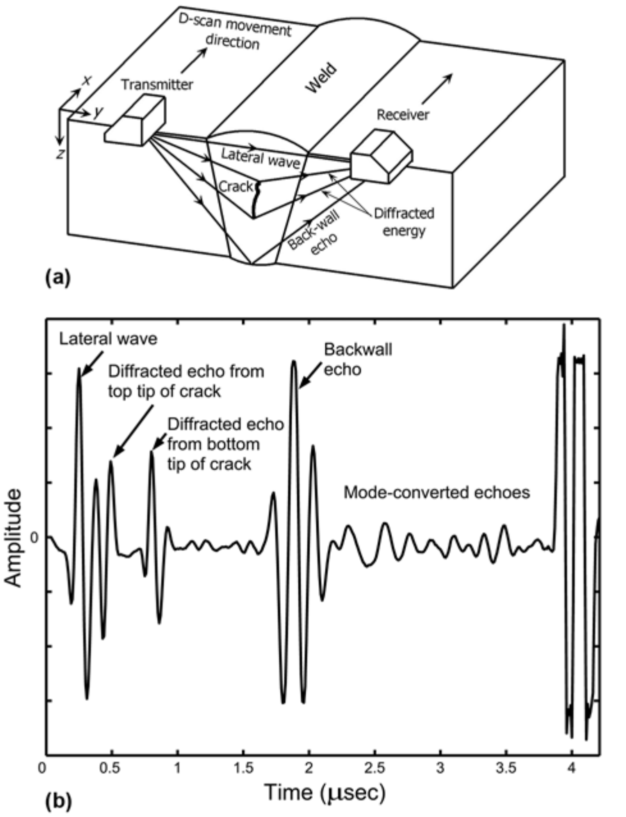

Figure 1. (a) Two probe transmitter-receiver arrangement for ultrasonic time-of-flight diffraction technique. (b) A-scan shows diffracted echoes

due to the fact that it is independent of defect orientation and easy to use. Echo amplitude is not used quantitatively by this technique for the determination of flaw size[(1)(6)].

3. Neural networks and fuzzy logic

In this research, three different artificial intelligence approaches were employed in the classification of weld defects. Neural networks with their ability to derive information from complicated and imprecise data can detect and extract patterns that can be too complex for simple systems. Fuzzy logic, proposed by Zadeh[(16-17)], is a theory that allows the natural descriptions, in linguistic terms, of problems to be solved rather than using numerical values. Fuzzy logic classifier was simplest to design and computational speed was much less. With membership functions, if-then rules and logical operators provided robust classifier. However, tuning membership functions with large volume of features proved to be its only disadvantage. A fuzzy-neural based classifier is a hybrid classifier with advantages of both neural networks and fuzzy logic. This classifier uses three-layer networks with the middle layer being for fuzzy if-then rules. The hybrid classifier is computationally fast and classification achieved is better than the other two classifiers. This is the classifier that learns from data and interpretable using fuzzy logic rules. Figure 2 shows a multilayer neural-fuzzy model and Figure 3 shows a typical output of a classifier giving defect characteristics. The accuracy and training of fuzzy-neural classifier is reliable and reproducible with statistical signal features.

4. Statistical textural analysis

Studies in psychophysics[(11)] investigates visual processes that allow humans to separate features in images are texture cues. A region in an image has a constant texture if a set of local statistics or other local properties of the picture function are constant or approximately periodic[(10)]. In this research several textural methods[(10-15)(18)] are investigated and implemented to greater success in the classification of defects. The range of methods used to extrapolate texture measures were auto-correlation, first order statistics, second order statistics (spatial grey level matrix), edge frequency, primitive length, Laws energy measures and segment based texture features. The classification was achieved by comparing each of these methods and then using best features using feature selection program. Haralick, *et al*[(12)] co-occurrence based matrix features is widely used in calculating texture measures. A novel approach, segment based texture measures uses idea extracted from first order statistics and co-occurrence matrix. This algorithm is computationally faster as first order statistics and provides more texture information as co-occurrence matrix. The texture features when combined with signal features provides very accurate and reliable automatic TOFD inspection system. Figure 4 shows texture patterns for different weld defects.

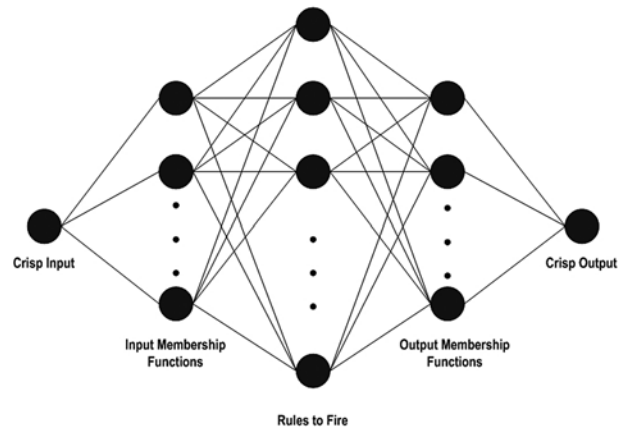

Figure 2. Multilayer neural-fuzzy network model

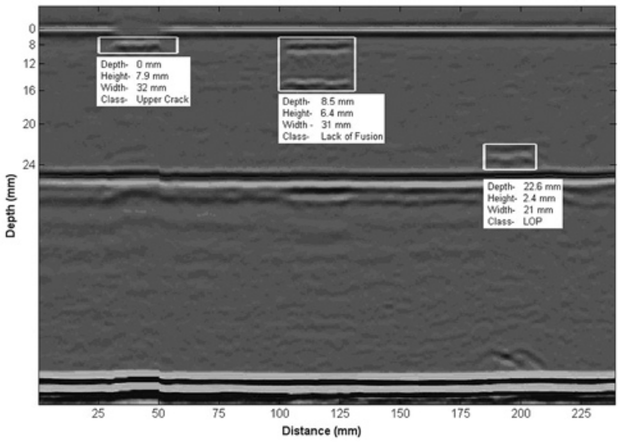

Figure 3. Automatic detection, sizing and classification of weld defects using TOFD technique

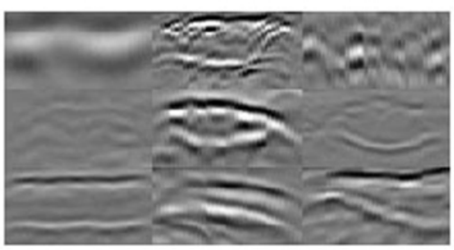

Figure 4. Different texture patterns for various detected defects

5. Importance of acceptance criteria and characterisation

The current standards[1][7][8] offers basic approach in characterisation of weld defects using TOFD technique. Conventional standards discriminates these flaws largely on basis such as size of flaw, location of flaw, phase relationship between defect signal and reference signal (lateral wave or back-wall signal), amplitude may provide important clue to the character of a flaw.

Lack of fusion, lack of penetration and slag lacks specific defect signatures in TOFD D-scan image due to several reasons[19]. Figures 5 and 6 show different complexities and defect signatures for lack of penetration flaws. The complexities involved in acceptance criteria[20] were researched. The acceptance criteria and standards must be agreed prior to an inspection and can be specific to an application. Some standards[1][19] can allow more discrete information and therefore describe cause of defects more precisely. Few European standards require acceptance criteria such that detection of defects is categorised as embedded flaws and surface flaws. However, a good standard and acceptance criteria must always give nature and cause of defect precisely which can act as a learning curve to avoid them in future welds.

6. Automatic segmentation and sizing

Until recently, TOFD has been a very accurate, fast and reliable technique in automatic detection and sizing[4][6-7]. The defect detection is achieved by local first order statistical properties of the TOFD images based on the variation in the intensity levels between pixels in the detected defected areas. The local variance in the defect regions was able to detect defects with 98% accuracy from the background. However, recently in this research segmentation was achieved using different texture methods. After detection position of lateral wave and back-wall signal allows accurate location and sizing of defects. The sizing features such as depth, height, width and aspect ratio along with the phase relationships between different echoes are important features in the classification of defects.

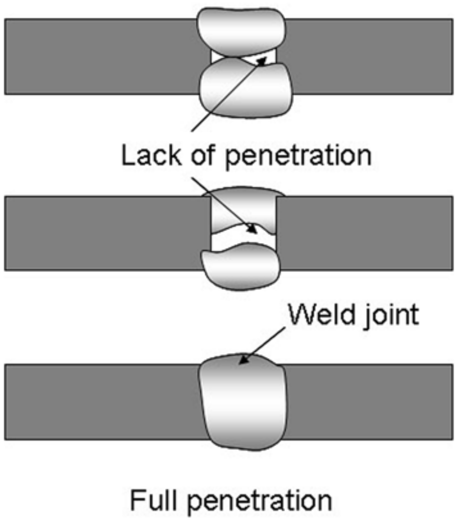

Figure 5. Two different models for lack of penetration giving two different defect signatures

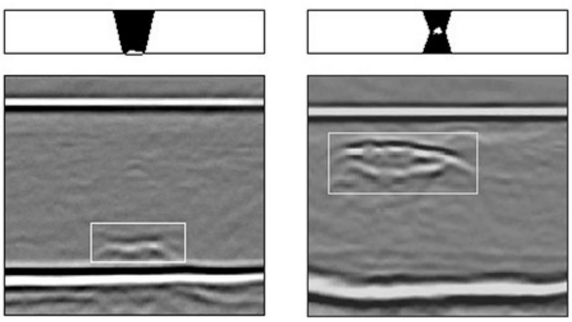

Figure 6. (a) Lack of root penetration. (b) Lack of complete penetration

7. Conclusions

The TOFD technique affords a fully automated inspection system for detection, interpretation and classification of weld defects. The developed neural-fuzzy classifier has shown exceptional promise, with the achieved results exhibiting high levels of accuracy, consistency and reliability, with acceptably low computational time. The fuzzy-neural based classifier provides better performance and combines the benefits of both neural networks and fuzzy logic. This will form the basis for a new paradigm in ultrasonics for fully-automatic batch processing and interpretation, thus presenting new opportunities for TOFD in automatic interpretation. Further details of the three classifiers are to be published elsewhere.

8. Acknowledgements

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