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Flexible decision support system for ultrasound evaluation of fiber–metal laminates implemented in a DSP

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ABSTRACT

Ultrasound testing has been widely applied for material characterization. The method accuracy usually relies on operator experience, considering this, an automatic decision support system may contribute to increase the evaluation efficiency. This paper presented an embedded electronic system for decision support in ultrasound evaluation of fiber–metal laminate composites. The proposed system comprised analog to digital conversion and digital signal processing algorithms. Discrete Fourier, wavelet and cosine transforms were used for feature extraction and principal component analysis was applied for efficient feature selection. The automatic classification was performed using an artificial neural network. The results demonstrated that it was possible to produce, in a short time latency, high-quality decision support information for two different types of test objects.

1. Introduction

Non-destructive evaluation (NDE) has been widely applied to reveal the internal characteristics of different materials. Among the most important NDE methods, ultrasound testing presents interesting characteristics such as high accuracy and a simple and safe execution procedure [1]. In many cases, the efficiency of ultrasound NDE had relied on the operator experience. The operator has been usually responsible for interpreting the measured signals and making a decision about the analyzed material properties. Among the applications of ultrasound evaluation there were corrosion monitoring [2], detection of defects in welded joints [3] and detection of structural cracks in metallic plates [4].

Composites are made through the union of different materials which are combined to obtain specific mechanical characteristics. This is the case for the fiber–metal laminates (FML), which are composed of thin metal plates alternately bonded to reinforced polymeric fibers [5]. The FML have been widely applied in the aeronautic industry due to characteristics such as low density, high stiffness, high corrosion resistance and low cost (when compared to aluminum alloys). A particular characteristic of FML is that they are susceptible to different failure mechanisms, which are related to both metallic and composite materials [5]. Considering the ultrasound evaluation, the superimposed thin-layer structure generates several propagation paths to the ultrasonic signal, resulting in an echo that is usually of difficult interpretation.

There had been some works devoted to design computational tools to support the operator analysis during ultrasound evaluations. For example, both a Fisher linear discriminant and a three-layered neural network were applied in [6] for the detection of weld defects in ferritic steel plates. The input parameters for the neural network classifier were pre-selected using the Fisher linear discriminant. The combination of wavelet decomposition and an artificial neural network classifier was used in [7] for detection of flaws in welded joints in thin steel plates. Different defects such as porosity, tungsten inclusion and lack of fusion were considered and high classification efficiency (approximately 94%) was achieved. Another application of neural networks for automatic ultrasound evaluation of welded joints could be found in [8]. Ultrasonic guided waves were used in [9] for the detection of small notch cuts in an ASTM-A53-F steel pipe. Wavelet, Hilbert and Fourier transforms were applied for feature extraction and an artificial neural network was used for automatic classification. This system showed good classification performance and robustness against noise.

Considering specifically composite materials, the work [10] investigated the sensitivity of features extracted from ultrasonic signals for the identification of typical pretreatment methods used in the aeronautic industry. In [11] discrete wavelet decomposition and principal component analysis were used for the extraction of

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relevant features of A-scan ultrasound signals of carbon fiber reinforced polymers. A support vector machine was applied for automatic classification of different types of defects such as delamination and porosity. The paper [12] used signal processing and different classification systems for automatic detection of defects in composite materials.

In most of the studies previously mentioned the time-domain ultrasound echoes were preprocessed before being used for material characterization. An interesting novel paradigm for signal processing of ultrasound signals was proposed in [13]. In that work time-domain ultrasound array data was used to obtain the scattering matrix, which was employed for the characterization of different types of crack-like defects. Considering an implementation in dedicated electronics (which was the case for our particular application) this approach might require high computational resources for simultaneously processing all the array signals.

In spite of the existence of high-efficiency decision support systems for ultrasound evaluation, most of them were implemented in computers which were not connected directly to the measurement equipment. In this case, the experimental data was usually recorded and analyzed (offline) to provide the decision support information. This aspect had limited the use of those systems during the evaluation procedure.

One of the main contributions of this work was that it presented an electronic system based on a digital signal processor (DSP) architecture that was designed to produce decision support information to the ultrasound operator during the evaluation procedure. The embedded signal processing chain comprised three stages. The first one was devoted to feature extraction, in which the raw data was processed using Fourier, wavelet or cosine transforms [14]. In the following, signal compaction (feature selection) was responsible for reducing the data dimensionality through a linear projection into principal components [15]. Finally, pattern classification was performed with a supervised multi-layer perceptron neural network [16]. The obtained results were presented to the operator through a liquid-crystal display (LCD). Another aspect of novelty present in this paper was the combination of different feature extraction algorithms to produce a high-efficiency classifier.

This document was organized as follows. In Section 2 the proposed electronic system architecture was described. The experimental setup used to validate the proposed system was presented in Section 3. The obtained results were detailed in Section 4 considering aspects such as the discrimination efficiency and the computational time. Finally, the conclusions and the suggestions for future works were presented in Section 5.

2. Proposed electronic system

The proposed electronic system comprised three main subsystems (see Fig. 1): the analog to digital converter (ADC), the digital signal processor (and its embedded algorithms for feature extraction, signal compaction and classification) and the user interface (liquid-crystal display – LCD). The main characteristics of these subsystems were presented in the following subsections.

2.1. Hardware specifications

Some embedded signal processing systems were proposed for ultrasound evaluation problems. For example, a hardware platform based on a field-programmable gates array (FPGA) was used in [17] for data acquisition in a multi-channel guided waves ultrasound test. The purpose was to develop a portable device for evaluation of pipelines. In [18] an automatic system based on an ARM microprocessor was used for ultrasonic evaluation of fruits.

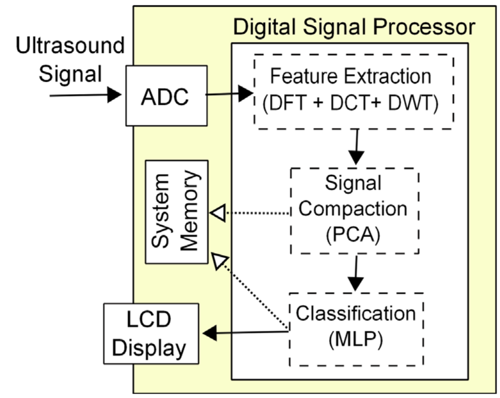

Fig. 1. Diagram of the proposed electronic system architecture.

Different signal processing techniques were applied to proper predict the fruits quality and integrity. A system-on-chip electronic design based on split-spectrum and neural networks was proposed in [19] to reveal the target ultrasound echoes in an intense noise environment.

The system proposed in this work was based on a digital signal processor (DSP) architecture. This choice allowed fast response and implementation of the digital signal processing algorithms using C programming language. The used DSP development board (TMS320C6713 [20]) operated at a clock-frequency of 225 MHz and had 192 KB of internal memory, 512 KB of flash memory and 16 MB of SDRAM. The use of the development board simplified the connection of external modules such as the ADC and the LCD. Its reduced dimensions allowed the construction of a portable device. When compared to FPGA based systems, a DSP design might be more flexible for modifications and upgrades, as it does not require the hardware synthesis procedure, only a firmware update.

2.2. Embedded digital signal processing techniques

The signal processing chain proposed in this work comprised different stages. The first one was a feature extraction module containing implementations of the Discrete Fourier, Wavelet and Cosine Transforms (respectively DFT, DWT and DCT). In the following there was a feature selection block based on principal component analysis (PCA). The final signal processing stage was a neural network classifier. An advantage of the proposed electronic system was that the user might customize the signal processing chain by choosing the more adequate configuration for a given problem.

In the following subsections a brief description of those algorithms was presented.

2.2.1. Feature extraction algorithms

In pattern recognition problems the feature extraction algorithms operate over raw (measured) data in order to make the relevant information more accessible. In this context, the Discrete Fourier Transform (DFT) of a discrete-time signal $y[n]$ provides the access to frequency-domain information [14]:

$$Y\left(e^{j(2\pi/N)k}\right) = \sum_{n=0}^{N-1} y[n]e^{-j(2\pi/N)kn}, \quad 0 \le k \le N-1. \tag{1}$$

For computational efficient estimation of the DFT a class of algorithms generally denominated Fast Fourier Transform (FFT) has been usually applied. In this work, a Radix-2 FFT implementation [14] was used.

The discrete cosine transform (DCT) [14] had also been used in feature extraction applications such as image processing and coding [21,22]. In some sense it is closely related to the DFT as it