Consistency Analysis of Ultrasound Echoes within a Dual Symmetric Path Inspection Framework

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Abstract—Non-destructive ultrasound inspection of metallic structures is a perpetual high-interest area of research because of its well-known benefits in industrial applications, especially from an economic point of view, where detection and localisation of defects in their most initial stages can help maintain high production capabilities for any enterprise. This paper is aimed at providing further validation regarding a new technique for detecting and localising defects in metals, the Matched Filter-based Dual Symmetric Path Inspection (MF-DSPI). This validation consists in demonstrating the consistency of the useful ultrasound echoes, within the framework of the MF-DSPI. A description of the MF-DSPI method and the related work of the authors with it are presented in this paper, along with an experimental setup used to obtain the data with which the useful echo consistency was studied. The four proposed methods are: signal envelope analysis, L2-norm criterion, correlation coefficient criterion and sliding bounding rectangle analysis. The aim of this paper is to verify the useful echo consistency (with the help of these four approaches), as the MF-DSPI method strongly relies on this feature. The results and their implications are discussed in the latter portion of this study.

Index Terms—non-destructive testing, automated inspection, matched filtering, echo analysis, signal processing.

I. INTRODUCTION

Minimizing the impact (e.g. costs) of defects in metallic structures is the ultimate objective of non-destructive ultrasound inspection, by detecting and localising these defects in the earliest of stages, when the costs of maintenance, repair and/or replacement are as reduced as possible. Thus, production activities are kept at a high, desired level.

Matched filtering is the preferred method, especially when using modulated excitation signals, which, generally speaking, are signals with a large bandwidth-duration product (such as linear frequency modulation, phase modulations, etc.). The pairing of matched filtering with modulated excitation signals is proven to offer the advantage of identifying signals in the presence of noise [1], while displaying a filtering gain proportional to the bandwidth-duration product. The improvements have been showed to be of 12 dB to 18 dB for chirps [linear frequency modulation (FM)], or in the range of 4 dB to 9 dB for non-linear FM and binary codes [2], [3].

On this foundation, the Matched Filter-based Dual Symmetric Path Inspection (MF-DSPI) method was recently introduced, which uses matched filtering in conjunction with stepped frequency signals which can be included in the larger "pseudo-chirp signals" class; the principles of this method will be described in Section II.

The MF-DSPI method supplies a set of two detection signals and takes advantage of the fact that only the useful echoes e.g. the defect and the backwall generated echoes, will be the consistent portions of the two signals with the motivation given in Section II [4].

In this paper we investigate this useful echo consistency with four methods, presented in Section III: sliding correlation coefficient window, using an approach inspired by us was used in [4], signal envelope analysis, L2-norm criterion and sliding bounding rectangle analysis.

The experimental setup e.g. steel block, equipment, signal parameters etc. is described in Section IV, and the discussion on the obtained experimental results and conclusions in Sections V and VI, respectively.

II. RELATED WORK AND THEORETICAL BACKGROUND

Several works investigated various aspects the theoretical and applicative of this topic, relating to: ultrasound matching filtering [5], ultrasound non-destructive testing [6], bounding rectangles [7-8] or correlation coefficients [9-10]. First of all, the matched filter is a linear time invariant (LTI) filter, which maximizes the receiver signal-to-noise ratio (SNR). By using the likelihood criterion, such a filter has the impulse response $h(t)$, equal to the input waveform, $s(t)$, which is time-reversed [1], [2]:

$$h(t) = k \cdot s(\tau_d - t)$$  \hspace{1cm} (1)

where $k$ is a gain factor and $\tau_d$ is the physical realisation generated time shift.

For the input $s(t)$, the matched filter output is given by equation (2):

$$x(\tau) = k \cdot R_{ss}(\tau - \tau_d)$$  \hspace{1cm} (2)

where $R_{ss}(\tau - \tau_d)$ is the time-shifted auto-correlation of the transmitted signal, $s(t)$.

Regarding ultrasound applications, the received signal
consists of several echoes, each displaying the same shape as the transmitted signals, but attenuated and corrupted by noise and false arrivals, including interferences, reflections by grains, etc. A cross-correlation between the transmitted, in our case, the stepped frequency signal, and the received signals will contain local maxima located at the time of arrival (TOA) of these echoes. The ideal context would be the presence of white noise, thus the matched filter output would be zero in the absence of echoes and would present maxima as the echoes arrive.

This was the previous work, upon which the Matched Filter-based Dual Symmetric Path Inspection (MF-DSPI) was introduced [4]. The methodology consists in acquiring two sets of sent-received pairs of signals: for a given fixed position of the ultrasound transducers, one set is for the transmitter-receiver configuration, while the second is obtained by switching the roles of the transducers leading to the transmitter becoming the receiver and vice versa, as can be seen in Figure 1. We shall name these configurations the "direct" and "inverse" configurations.

The motivation for this approach is the fact that the two received signals will certainly contain the two echoes of interest which are generated by the defect and the backwall, respectively, while keeping consistent properties: detection signal shape and TOA, also, there will be a plethora of false-alarm echoes, caused by metal impurities, but these echoes, when comparing the two detection signals, will exhibit different behaviours, in signal shape and/or TOA. This is because the sources of these echoes stemming from the metal impurities – coarse grain structure, have different relative positions to and from the transducers, which lead to different reflection/refraction geometries. An important aspect is the fact that defect generated echoes will have a reduced TOA, compared to the TOA of the backwall generated echo, thus the search for the defect will be optimized by carefully selecting the portion of the signal only until right after the backwall generated echo, including it, in order to have a correct reference available. After carefully selecting the portion of interest from the signals, the next step is to use a sliding time-frequency mask, which shifts through the two received signals, as shown in Figures 2 and 3.

The approach for building the time-frequency mask is the following:

- time mask: selecting the time intervals that match the time pattern of the excitation signal, in this case, 11 chirps – linear FM signals, Figures 2 and 3;
- frequency mask: selecting the frequency intervals, this time based on the frequency pattern of the components of the excitation signals, again, 11 chirps, selected with the use of Butterworth pass-band filters – Figures 2-3.

The exact parameters of the excitation signals that were used will be presented in section IV, concerning the experimental setup. Explanations regarding the time-frequency mask and the matched filtering (MF) used by the MF-DSPI are given by [4]. This paper is aimed at studying the consistency of the useful echoes, as stated before.

### III. Echo Consistency Analysis

#### A. Signal Envelope Analysis

This method consists in analysing the envelopes of the two detection signals supplied by the MF-DSPI. The envelope is obtained with the help of the analytic signals $y_i(t)$, for each of the detection signals $d_i(t)$ and $d_2(t)$:

$$y_i(t) = d_i(t) + j \cdot \text{Hilbert} \{d_i(t)\}$$

where $i=1,2$ and $\text{Hilbert} \{\cdot\}$ denotes the Hilbert transform [11]:

$$H\{x(t)\} = \frac{1}{\pi} p.v. \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau$$

where $p.v.$ represents the Cauchy principal value.

The envelopes are calculated with the help of the following formula:

$$e_i(t) = \left\Vert y_i(t) \right\Vert$$

The analysis is carried out on each of the two detection signal envelopes. We impose the empiric criterion of selecting only the values over a certain threshold computed as a small enough percentage of the highest value from each of the envelopes, corresponding to the backwall echo. Also, we require that simultaneous samples have approximately equal values.
These criteria are explained in equation (5), for a given sample $y[k]$ of one of the two envelopes:

$$\begin{align*}
y_1[k] &\geq y_{\text{threshold}} \\
y_2[k] &\geq y_{\text{threshold}}
\end{align*} \quad (6)$$

This method enables us to select only the consistent portions of the two detection signals. By "consistent" we understand the portions of the signals which have the same signature (shape) and have the same TOA e.g. "positioning" in the time domain.

B. L2-norm Criterion

For this method, the analysis is performed with a sliding 5-element window, through each of the two signals, in the same time, and for each position of the window, the L2 – norm [12] for the two 5-element sequences is calculated. Equation (6) shows how this criterion is evaluated at a given position $k$ in each of the two detection signals:

$$y_1[k] - y_2[k] = \sqrt{(y_1[k] - y_1[k])^2 + \ldots + (y_1[k+n] - y_2[k+n])^2} \quad (7)$$

and the two norms should be approximately equal, in order to consider the 5-element sequences consistent:

$$\|y_1[k:k+4]\|_2 \approx \|y_2[k:k+4]\|_2 \quad (8)$$

C. Sliding Correlation Coefficient Window

This window was chosen to be 10 elements wide i.e. 1 microsecond, because the objective was to make it smaller than half the width of the backwall generated echo i.e. 2.5 microseconds, which was used as a reference, in order to have a sufficient analysis resolution. The window slides through the two detection signals supplied by the MF-DSPI, and checks the consistent segments e.g. the useful echoes by calculating the correlation coefficient [13] between the two 10-element sequences, $d_{10}^{i10}$ and $d_{10}^{i10}$, for iteration $i$:

$$R_{d_{10}^{i10},d_{10}^{i10}} = \frac{\sum_{j=1}^{i+9}(d_{10}^{i10}[j]-\bar{d}_{10}^{i10})(d_{10}^{i10}[j]-\bar{d}_{10}^{i10})}{\sum_{j=1}^{i+9}(d_{10}^{i10}[j]-\bar{d}_{10}^{i10})^2 \sum_{j=1}^{i+9}(d_{10}^{i10}[j]-\bar{d}_{10}^{i10})^2} \quad (9)$$

where $\bar{d}_{10}^{i10}$ and $\bar{d}_{10}^{i10}$ are the sample means of the shifting (sliding) window sequences. Sequence consistency was considered valid when the correlation coefficient satisfies:

$$R_{d_{10}^{i10},d_{10}^{i10}} > 0.95 \quad (10)$$

in the interest of eliminating non-consistent sequences from the two detection signals e.g. false alarm echoes.

D. Sliding Bounding Rectangle Analysis

The bounding rectangle [14] was considered to be of length 2.5 microseconds (25 elements), the same as the duration of the backwall generated reference echo. This rectangle is shifted through the two detection signals and its area is computed as follows:

$$A_i^{25} = \max(d_{i}^{25}) \times \min(d_{i}^{25}) \quad (11)$$

Consistency is obtained for approximately equal values of these areas:

$$A_i^{25} \approx A_i^{25} \quad (12)$$

The sequences where the two sliding bounding rectangles coincide are the sequences of similar shape and identical TOA’s. Thus, they are considered to be consistent.

IV. EXPERIMENTAL SETUP

In order to carry out our study, we used a steel block with a non-homogenous, coarse grained structure resulting from a low quality block of steel. It displayed a high attenuation of the ultrasound energy and also a high number of randomly distributed scatterers, which increased the rate of false alarm echoes. In addition to these features, the defects aimed for detection and localisation were longitudinal e.g. parallel to the ultrasound transmitted signals, which made the aforementioned objective more difficult (Figure 4).

The steel block that was used to verify and compare the two methods was a non-homogenous, low quality block of steel, with a coarse grain structure. Because of this, the attenuation of the ultrasound signals was higher, and the presence of randomly distributed scatterers introduced the increased rate of false alarms. Also, the defects which we tried to detect and localise were longitudinal, as seen in Figure 4, parallel to the ultrasound excitation signals, thus increasing the difficulty of the test case scenario.

The two defects of interest had these features, given the measured ultrasound velocity in the steel block was averaged at about 5.52-5.53 millimeter per microsecond:

- 1$^{st}$ defect: height $h_1 = 30$ mm and expected time $t_1 = 26$ microseconds;
- 2$^{nd}$ defect: height $h_2 = 25$ mm and expected time $t_2 = 28.5$ microseconds;

The central frequency of the ultrasound transducers is 1 MHz. The two transducers were connected to an acquisition board; the emitter was also connected to a PC controlled signal generator, and the acquisition board was connected via USB to a portable computer, which ran an oscilloscope-type software, able to depict the signals in real time and also to save them in a .mat format.

The modulated excitation signal used was a stepped frequency modulation, a pseudo-chirp (Figure 2), with the
following properties:

- 11 chirps, with a 30 KHz bandwidth, centred at the following frequencies: 750 KHz, 800 KHz, 850 KHz, 900 KHz, 950 KHz, 1000 KHz, 1050 KHz, 1100 KHz, 1150 KHz, 1200 KHz, 1250 KHz;
- chirp duration: 15 microseconds; time between chirps: 100 microseconds; sampling frequency: 10 MHz;
- entire signal repetition period: 13.1 milliseconds, enough time to avoid residual echoes, according to the block of steel used - Figure 5;
- designed and adapted to avoid multiple scattering by careful choice of the frequency domain [15].

V. EXPERIMENTAL RESULTS

First of all, the two detection signals supplied by the MF-DSPI method are shown in Figures 5 and 6. These include both the direct and inverse paths.

For the first and largest defect (Figure 5) one can notice a certain presence at around 26 microseconds. For the second and smaller one (Figure 6), the detection signals are corrupted with false alarm echoes, and thus the consistency analysis is absolutely crucial in determining the presence and location of the defects.

A. Signal Envelope Analysis

The results for the signal envelope analysis methods are shown in Figure 7 (defect 1) and in Figure 8 (defect 2).

The results strongly point that the only consistent sequences from the two detection signal envelopes, are those corresponding to the useful echoes, indicating the presence of defect 1 at 25.8 microseconds and defect 2 at 29.1 microseconds, which correspond almost perfectly with the analytical (real) values, presented in Section IV.

B. L2-norm Criterion

The consistency analysis results, for the L2-norm criterion, are shown in figure 9 and in figure 10.

The results clearly indicate the increased difficulty in detecting and localising the smaller defect (cavity number 2 – Figure 10). But nevertheless, the L2-norm test is sufficiently strong to reveal in either cases that the useful echoes are consistent with one another.
The disadvantage for this method is that the results show also a generally increased amount of false alarm echoes that this method has selected as being consistent. Although the false alarm echoes are significantly smaller than the useful ones, their presence tends to reduce the overall efficiency of the \( L_2 \)-norm criterion approach.

C. Sliding Correlation Coefficient Window

Figure 11 and Figure 12 present the results of using the sliding correlation coefficient window approach. This was also used and suggested in [4].

The results are indicating, again, a strong consistency of the useful echoes, as they are visible at 29.4 microseconds and 26.2 microseconds for Defect 2 and Defect 1, respectively, which are strongly similar to the real, analytical values.

D. Sliding Bounding Rectangle Analysis

The results for this method are shown in Figures 13-14.

Figure 13 shows how the sliding bounding rectangles method manages to select almost exclusively the consistent sequences from the two detection signals, as the backwall generated echo is correctly located at 35.7 microseconds (≈ 36 microseconds, the calculated value, based on the steel block dimensions and averaged ultrasound velocity), and the Defect 1 generated echo is also correctly pinpointed at 26.2 microseconds. There is also a small false alarm echo, as it was the case with Defect 2 (Figure 14), but the overall sizes are extremely low when compared to the useful consistent echoes. Figure 14 also correctly indicates the presence of Defect 2 at about 29 microseconds, the expected value.

E. Comparative Analysis

The paper presented a multiple approach to the study of echo consistency, within the framework of the MF-DSPI method. As the MF-DSPI is strongly based on the principle of consistency (similarity, regarding signature shape and also TOA), this principle was successfully verified with the help of the four proposed methods. A threshold range for which the probability of detection is 1 (detection of both defects, with four final detection signals) and probability of false alarm is 0, including range width, is given in Table 1.

It should be noted the higher difficulty for the smaller defect, as was the case for the \( L_2 \) – norm method, in the sense that figure 12 also indicates a false alarm echo, at about 14 microseconds. But considering the small size of this false alarm echo, the results for the sliding correlation coefficient window method are very promising.
TABLE I. METHOD COMPAREION

<table>
<thead>
<tr>
<th>Method</th>
<th>Observations on efficiency</th>
<th>Threshold range</th>
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<tbody>
<tr>
<td>Signal Envelope Analysis</td>
<td>This proved to be the most robust method. NO false alarm echoes passed the consistency check, selection of only truly consistent echoes. Best performance.</td>
<td>0&lt;Threshold=0.291 Range width = 0.291</td>
</tr>
<tr>
<td>L2-norm Criterion</td>
<td>This method pointed strongly to the correct assumption of consistency regarding useful echoes, but selection criteria was not strong enough to avoid selection of false alarms. Worst performance.</td>
<td>0.19&lt;Threshold=0.2 Range width = 0.09</td>
</tr>
<tr>
<td>Sliding Correlation Coefficient Window</td>
<td>The initial method for consistency check. Results show very good ability detecting consistency. Very low false alarm influence. Very good results.</td>
<td>0.14&lt;Threshold=0.2 85 Range width = 0.145</td>
</tr>
<tr>
<td>Sliding Bounding Rectangle Window</td>
<td>Very powerful method in detecting the consistency of the useful echoes. Results similar to the sliding correlation coefficient window. Very low false alarm presence. Consistency validated. Very good results.</td>
<td>0.083&lt;Threshold=0.2 217 Range width = 0.13</td>
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</table>

VI. CONCLUSION

In conclusion, fault detection in industrial applications presents a very active field of research, involving advanced methods for signal processing [16], [17]. In this work we have visibly demonstrated the consistency of the useful echoes with the use of the previous multiple approach, thus further validating the promising nature of the MF-DSPI method. The results show a clear reduction (in one case, total reduction) of the false alarm echoes, and clearly permits the successful inspection for detecting and locating defects in metallic structures. The advantages of this method consist in its ability to perform analysis on more difficult environments, like coarse-grained steel structures, with high attenuations, and even in cases where the defects are longitudinal (the steel block which was used for the previous experimental validation). Future work will focus on other aspects related to the MF-DSPI method: the design of more efficient frequency modulations and the use of an adaptive time-frequency pattern for the excitation signals, which can maximize the information extracted from the ultrasound inspection of metallic structure. Also we aim the expansion of this method to other mediums, such as concrete, although concrete may require another approach, considering the granularities from its coarse-grained structure are of large dimensions that those from the current steel block.

Another objective to be studied further is a multi-transducer configuration on a didactic and research platform [18-20], which would better exploit the principle of consistency used by the MF-DSPI method. In theory, having more than two detection signals, from a multi-transducer configuration, can improve the strength of the consistency criteria, thus reducing the impact of false alarm echoes.

REFERENCES


