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Cracks and Welds Detection Approach in Solar Receiver Tubes Employing EMATs

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Abstract

There is a significant rising in development of new Concentrated Solar Plants (CSP) due to global energy demands. CSP requires to improve the operational and maintainability in this industry. This paper presents a new approach to identify defects in the solar receiver tubes and welds employing a simple electro-magnetic acoustic transducers (EMAT). The absorber tubes in normal working conditions must withstand high temperatures, which can cause that the tubes to deteriorate in areas such as welding, or it can cause hot spots due to defects or corrosion. A proper predictive maintenance program for the absorber pipes is required to detect defects in the tubes at an early stage, reducing corrective maintenance costs and increasing the reliability, availability, and safety of the concentrator solar plant. This paper presents a novel approach based on signal processing and pattern recognition for predictive maintenance employing EMATs. Hilbert Transform is used to obtain the envelope of the signal, that is smoothed by wavelet transform. It reduces the probability of detecting false positive alarms. The algorithm uses the distance of the sensors from the edges to perform a self-identification of signal events. The events are located using two possible ways of ultrasound propagation, forward and reverse, and the time of flight of each echo. The algorithm correlates the theoretical events with events founds experimentally. These echoes could come from different paths due to the EMAT generates forward and reverse Shear Waves. The main novelty in this approach is that the location of the defect can be determined considering two echoes that come from the same defect, but they arrive to the sensor flowing by different paths. The results obtained with a double validation by matching the echoes that meet certain conditions. It increases the accuracy of the inspection and reduces false alarms. The approach has been tested and validated in an experimental platform that simulates the concentrator solar plants.

Keywords: Fault Detection and Diagnosis, Wavelet Transforms, Non Destructive Tests, Concentrator Solar Plants, Condition Monitoring, Structural Health Monitoring.

1. Introduction

The dependence on electricity produced from fossil fuels and nuclear power plants in the world has remained unchanged in recent decades, despite the introduction of energy from wind and solar farms. Due to the continuous growth in electricity needs and the political interest to reduce the gas emission, mainly from the Kyoto protocol, renewable energy sources has been used to cover the world energy demand. Concentrated Solar Plants (CSP) is an alternative to onshore wind and photovoltaic farms.

The European solar thermal energy industry is having a rapid growth rate to meet the increasing environmental, societal and economic demands. The annual turnover of the European solar thermal power industry and its added value was 12 billion € for 2011, and it is expected that by 2020 the CSP market could be more than 55 billion €. Figure 1 shows the growth of solar thermal power generation in the world between 2015 and 2050.

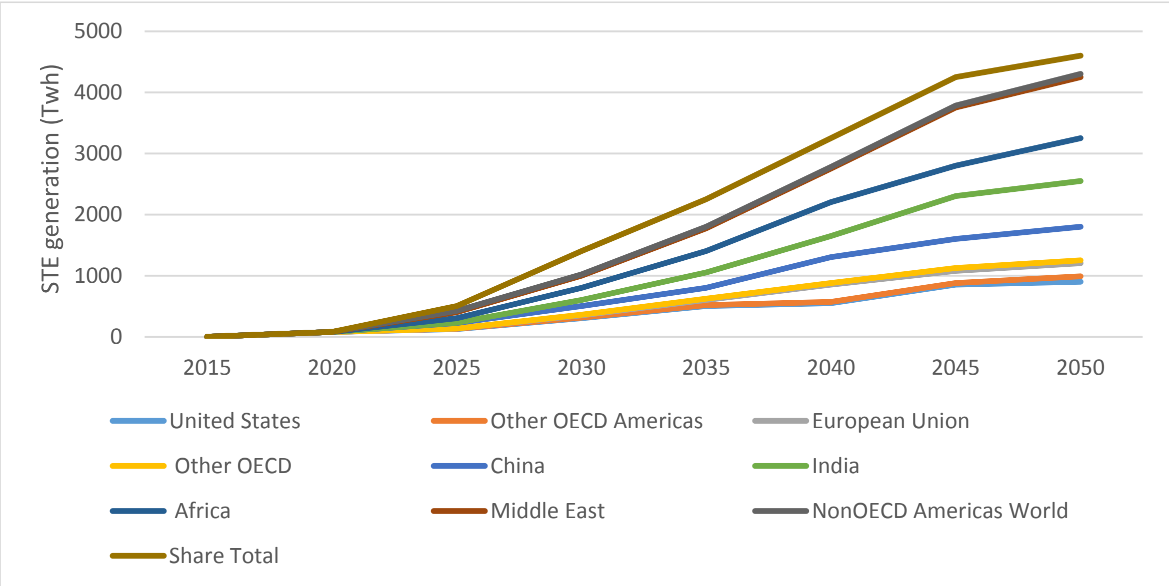

Figure 1. Solar thermal power generation capacity in the World 2015-2050 [1].

Solar thermal energy provides a small fraction (less than 0.2%) of the overall European electricity production. However, with the current growth trends exhibited the solar thermal energy industry will supply more than 10% of the overall European power production by 2030, and over 25% by 2050, and is expected to be almost half of the solar thermal energy produced worldwide by 2020 [2,3]. Over the next decade, this industry is expected to be double of the annual growth rate that the wind energy industry [4].

Molten salt-based CSP plants can operate in regions where water resources are critical, particularly for the Mediterranean and African countries.

Non-destructive testing (NDT) for fault detection and diagnosis (FDD) in structures has more importance nowadays due to the advances in instrumentation technology and digital signal processing [5-7]. Techniques for structural health monitoring (SHM) leads the FDD and their location on the basis of changes in static and dynamic structural features [8]. The capability of NDT to prevent the evolution of faults to catastrophic failures is one of its main advantages, resulting in the achievement of better reliability, availability, maintainability and overall cost reduction of the system [9,10].

Guided waves are a common technique employed for SHM into the NDT field [11-13]. This technology is based on the excitation of low frequency ultrasonic waves flowing along the pipeline over long distances. It allows inspections of large pipes without any relocation of the interrogating unit [14].

The cost of Linear Fresnel Receivers can reach 30% of the overall CSP cost. Therefore, the correct maintenance of the receivers is important to assure the competitiveness of a CSP [15-18]. The average annual Parabolic Trough Receivers (PTR) replacement rate was about 5.5% in the first years of CSP (1997-2001) [19]. Nowadays, it has been reduced to 3.37 % [20], and forecasts indicate that the replacement rates could decrease up to 0.5 %.

The overheating, or tube thinning, has been analyzed by thermographic inspection [21]. The thermograms got by infrared cameras are unreliable because of the presence of the glass envelope and cermet coating.

Magnetic Flux Leakage, Eddy Current Testing, Ultrasonic Testing, etc., are employed as conventional Nondestructive Evaluation to inspect insulated pipes [14]. The removal of pipe insulation is time-consuming and can potentially result in damage to both pipes and insulation. Moreover, removal of the insulation is only safe during plant shutdown, since corroded or cracked pipelines may rupture during the removal process while they are still in-service, posing an unacceptable risk to the safety of maintenance engineers.

Tangential radiography can be applied for the detection of corrosion in in-service pipelines without the need of removing the insulation [22]. However, its use involves health and safety considerations and, therefore, exclusion zones need to be imposed before radiographic inspection can begin. It is also impossible to inspect every single section of insulated piping.

Conventional Long Range Ultrasonic Testing (LRUT), or guided waves, based on piezoelectric transducers on the other hand, can be employed for the inspection of long section of insulated pipes but only during a planned outage [23]. The installation of the inflatable ring containing the piezoelectric transducers also requires the removal of the insulation in the area that the ring is mounted on. Since there is always a risk of pipe rupture, the ring can only be safely installed when the pipe is out of service. Even if the pipe is known to be defect free, the piezoelectric elements (typically lead zirconate titanate or PZT crystals) and inflatable ring are not designed to operate at temperatures above 120°C, that is much lower than the operational temperatures of in-service CSP pipelines.

LRUT based on EMATs can be applied without the need of physical contact of the sensors with the inspected tube or surface. EMATs operate to long distance and can be also designed with a cooling circuit to maintain their temperature constant always. EMAT design is simple, consisting of a rare earth magnet or DC electromagnet and a coil excited by an alternating current fed at ultrasonic frequencies [24-26]. In contrast, piezoelectric transducers are much more expensive (>€300/unit), and their performance deteriorates with time, particularly when operating at adverse environmental conditions. The quality of the piezoelectric elements also needs to be assessed to ensure an acceptable level of consistency from batch to batch. EMAT rings can be permanently attached in the area of interest to continuously monitor a section of the solar receiver tubing or insulated piping regardless of the operational temperature at very low cost and without the need for ever carrying any maintenance on the inspection unit after installation.

Structural defects found in solar receivers and insulated pipes can be classified either as critical or non-critical. Non-critical defects are those which do not compromise imminently the structural integrity of the solar receivers and insulated piping or the safety of CSP plant operations. Critical defects are those which can unexpectedly result in failure of the solar receiver and pipes, potentially compromising the power generation process [14].

The purpose of this work is to design a FDD [27-30] model using ultrasound signals, together with advanced signal processing methods, to monitor the structural assessment of PTR in a CSP [25,31-33].

The NDT used is based on long range ultrasonic, also known as guided waves, based on the use of ultrasonic waves traveling along the surface to be inspected, in this case, austenitic stainless-steel pipes. It is possible to find any defect or change in the structure, since these defects returns an echo, which is recorded by a sensor.

The main objective of the experiments is to detect changes in the thickness of the pipe. The changes on the thickness may be due to welding or defects, e.g. cracks or corrosion in the pipe. A novel algorithm has been designed to detect in the tubes this type of defects and to locate them.

A wavelet-based algorithm has been designed and applied to EMAT signals. De-noising algorithm has been applied to improve the signal-to noise ratio (SNR), without introducing time delay in the original signals. In contrast to other digital filters, the wavelet de-noising filter does not produce an undesired signal delay.

Hilbert Transform is used to obtain the envelope of the signal. The envelope for finding events in the signal that appear as peaks is smooth by wavelet transforms. The algorithm uses the distance of the sensors from the edges to perform a self-identification of signal events. The main novelty in this new approach is that the events are located using two possible ways of ultrasounds propagation, forward and reverse, and the time of flight (ToF) of each echo. The algorithm correlates the theoretical events with events founds experimentally. It increases the accuracy of the method and it is also employed to validate the results. These echoes could come from different paths due to the EMAT generates forward and reverse Shear waves. The existence of the defect and its location are determined.

2. Case Study

2.1. Test Rig

The main purpose of the case study is to test in a laboratory for the detection, localization and characterization of structural defects in pipes of CSP. A test rig has been designed and constructed to simulate the conditions of a PTR, and create similar temperature and thermo-mechanical fatigue conditions. The test rig consists in an oil heater, the circulation pump, the storage tank and a control panel. It has two 4 m long stainless-steel tube samples. It can be simulated for temperature conditions, cracks, welds faults, or flows. The main components of the test rig are:

- Special steel pipes and elbows designed for high temperature.
- Pumping and heating systems for working with different fluids: water or oil.
- Heating system

The schematic of the CSP test rig is shown in Figure 2.

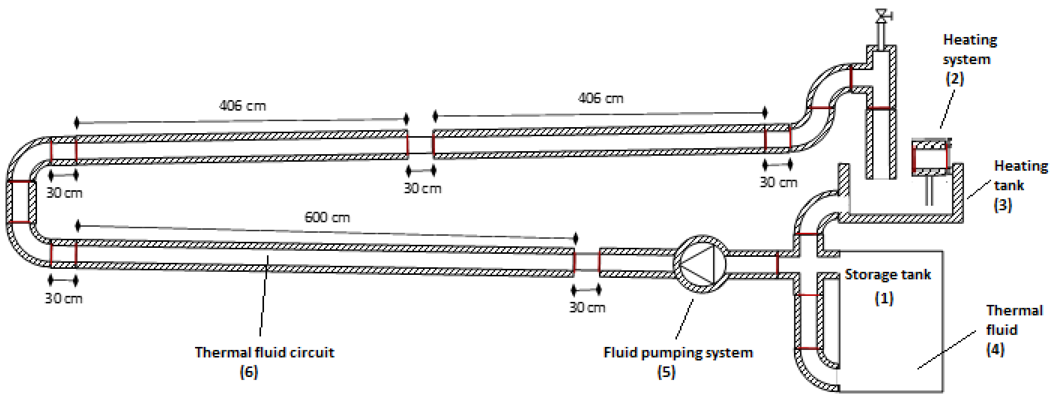

Figure 2. Schematic of the CSP test rig

Figure 3 shows the real CSP test rig employed in the experiments.

Figure 3. CSP test rig.

The test rig is compound by two sections of pipe, one for warming, which simulate the circuit portion that absorbs solar radiation in a CSP, and return section, being the tubes of austenitic stainless steel. The ultrasonic waves are studied in the first section. The dimensions of the plant have been selected to reproduce at least two sections of solar collectors in actual installations, i.e. two 4.06 meters tubes welded to a connector of the same type of steel. The connector space is used to support the pipe by metal arms attached to the pillars supporting the reflecting mirrors. This space is considered ideal to place the transmitter / receiver of ultrasonic waves (see Figure 4).

(a) (b)

Figure 4. Detail of the junction of the collector tubes in the experimental platform (a) and in a real CSP in Almeria, Spain (b).

The test rig allows to study the influence of the welds on the transmission of ultrasonic waves, and the distance travelled by the waves over 8 meters. The length of the tube, that is monitored by a pair of EMAT Tx and Rx, is more than 4 meters. Figure 5 shows the displacement distribution on a 4 meters absorber tube with two transmitters. It was found that one transmitter can cover the length of the pipe for defect detection, but two or four transmitters are required to cover the pipe.

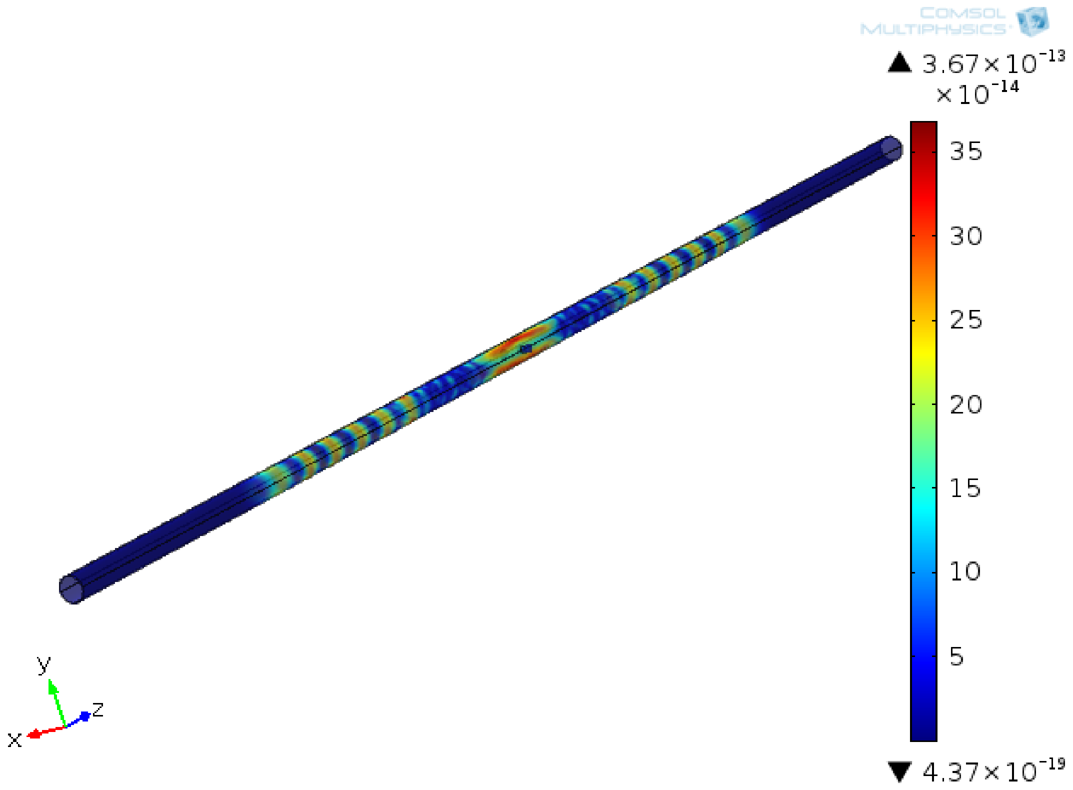

Figure 5. Displacement distribution on 4-metre pipe with two transmitters at 400µs

The main objective of the experiments is to detect changes in the thickness of the pipe. The changes on the thickness may be due to welding or defects, e.g. cracks or corrosion in the pipe. A novel signal processing approach has been designed to detect in the tubes this type of defects and to locate them.

3. Signal Processing Approach

A wavelet-based algorithm has been designed and applied to EMAT signals. De-noising algorithm has been applied to improve SNR without introducing time delay in the original signals [34]. Figure 6 shows the original signal and the de-noised signal after applied different de-noised filters. In contrast to other digital filters, the wavelet de-noising filter does not produce an undesired signal delay [35,36].

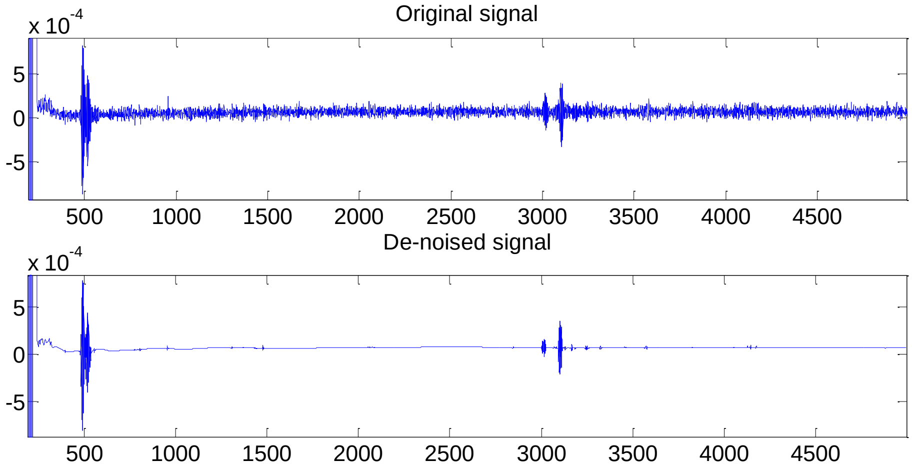

Figure 6. Wavelet decomposition detail eleven (D11) (upper panel), and de-noised D11 and extracted residual noise signal with two welds (bottom panel).

It is observed that the filter removes noise significantly, and it also does not eliminate events occurring in the signal with a specific frequency.

Hilbert Transform is used to obtain the envelope of the signal. It is necessary to smooth the envelope for finding events in the signal that appear as peaks. It reduces the probability of detecting false positives. The smoothing must not eliminate small peaks.

3.1. Cracks detection and edges location

A novel method is presented in this section for cracks detection and edges location, where the process is shown in Figure 15, and it is based on:

- *Peak searching*: It is necessary to select a proper threshold.
- *Identify echoes from the edges*: The time of flight (ToF) of each echo is obtained and compared with the distances of the sensor and actuator according to the boundaries according to the scheme shows in Figure 7.

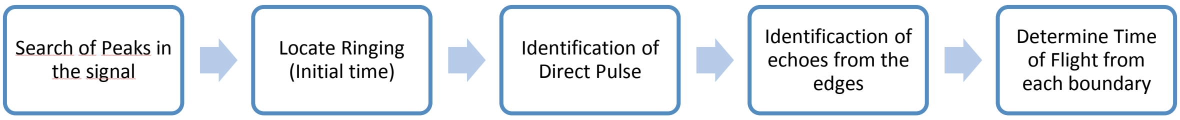

Figure 7. Identification of edges echoes scheme.

- Theoretical and experimental comparison for identification of the boundaries (see Figure 8).

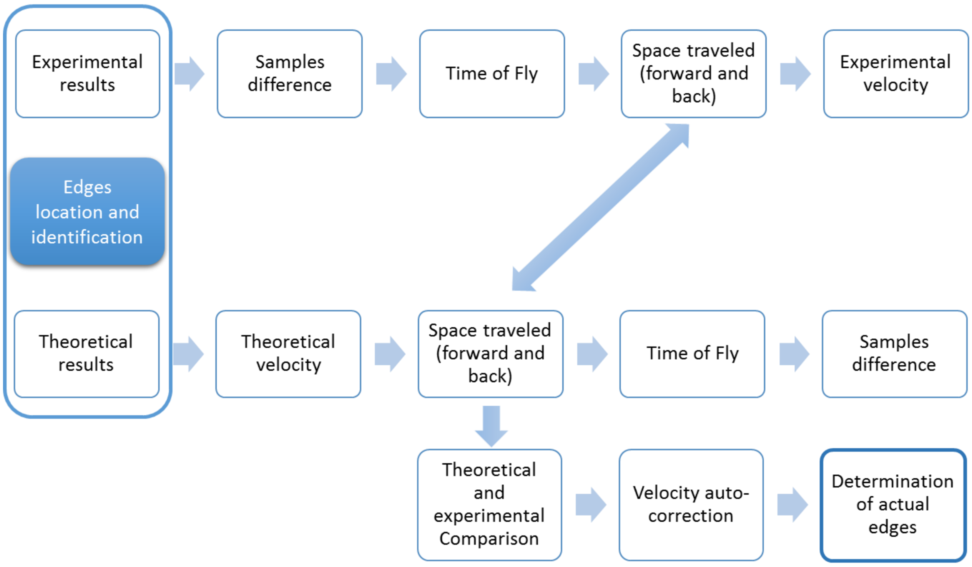

Figure 8. Theoretical and experimental comparison for edges identification.

False cracks require to be reduced, and they also provide information such as the attenuation of the ultrasonic wave propagation along the material. The algorithm uses the distance of the sensors from the edges to perform a self-identification of signal events. The events are located using two possible ways of the ultrasound propagation, forward and reverse, and the ToF of each echo. The algorithm correlates the theoretical events with events found experimentally. These echoes could come from different paths due to the EMAT generates forward and reverse Shear waves (Figure 9).

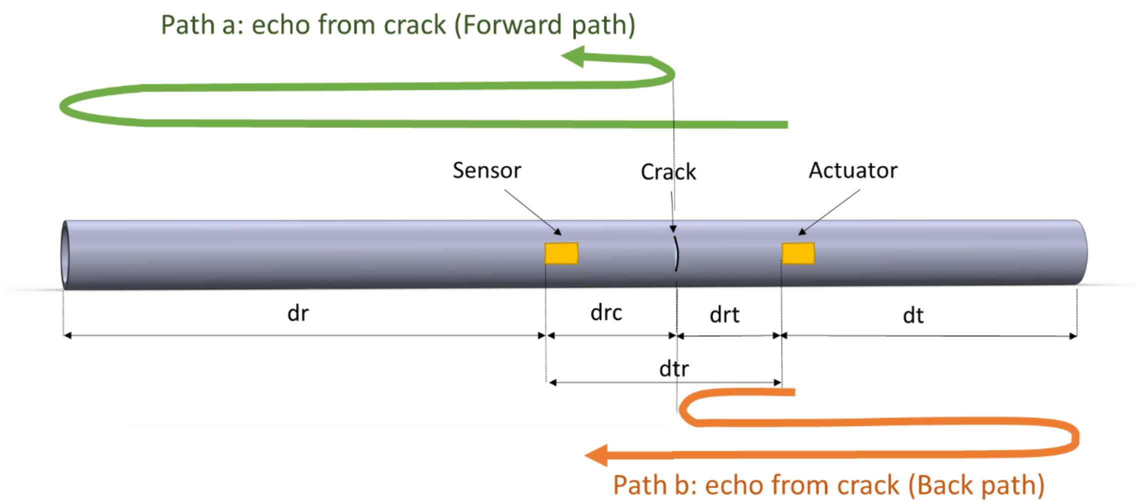

Figure 9. Two shortest paths from actuator to sensor detecting the crack.

The method detects cracks analyzing the ToF employed by the same pulse that travels by two different paths. The existence of the defect and its location can be determined if the distance travelled by both paths are the same. The method scheme is shown in Figure 10.

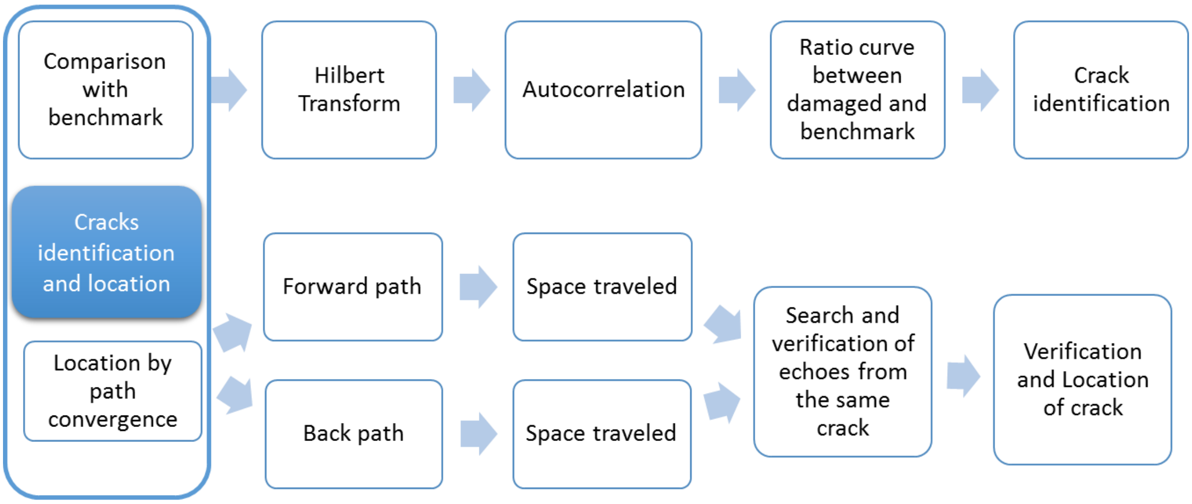

Figure 10. Location of the crack by two methods: Comparison with benchmark and location by convergence of different paths.

4. Results

Two experiments were performed in the test rig to determine the effectiveness for detecting discontinuities in the tube: The first experiment was carried out to detect and locate a crack in the pipe, and; the second experiment was made to detect and locate welding in the pipeline. The EMAT transducer was excited to 256 kHz and 6 cycles. The pipe line employed in this experiment has 75 mm of diameter, 2 m of length and 3.05 mm of thickness.

4.1. Crack detection and location.

A defect has been induced on the pipe to visualize the automatic location of the defects. It was induced a cut of 1mm of thickness, 2mm of depth and 3cm of length to generate a defect that simulates a crack on the pipe. Figure 11 shows the placement of the EMAT and the crack location. The EMAT (transmitter) generates Shear waves in both directions (forward and back). The EMAT (sensor) receives the direct pulse and the echoes from the edges and from the crack.
The experiment was done 10 times obtaining the same results. The received signals were processed and analyzed.

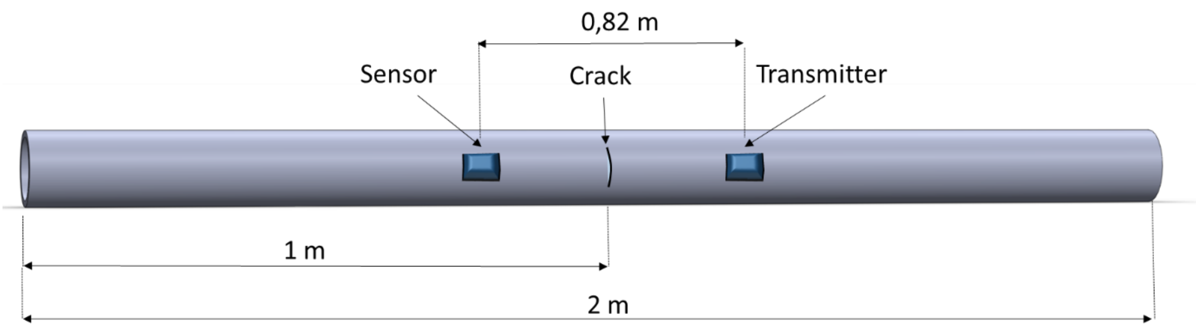

Figure 11. EMAT's placement to detect the crack in the absorber pipe (316L steel).

The signal obtained considering a crack is shown in Figure 12, where the numbers 1-4 identify:

1. The direct pulse (the shorter distance between the actuator and the sensor).
2. The first reflection from the front edge.
3. The first reflection from the back edge.
4. The crack refection.

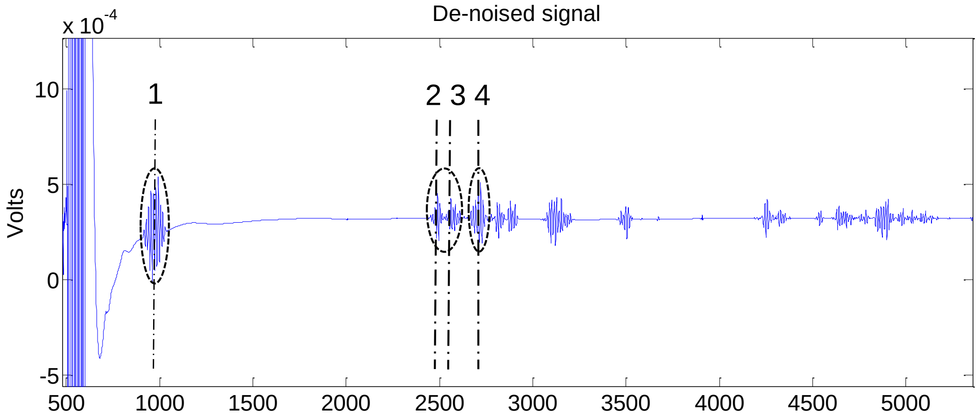

Figure 12. Edges and crack reflections of Shear waves by comparing the theoretical and experimental values of ToF.

The algorithm detects the echo 4 as a potential crack, and determine that it has traveled by the forward path. It is possible to find the point where the echo was reflected in the crack with this information, i.e. the exact point where the defect is located. Then it is shown the location of the crack. Figure 13 presents the results in a schema with the current dimensions of the pipe, the position of the transducers and the defect location. The approach does a double validation of the existence of the defect as main novelty, by detecting the same crack by different paths. However, it does not determine the size or depth of the crack. It can be performed employing complementary methods [37-39].

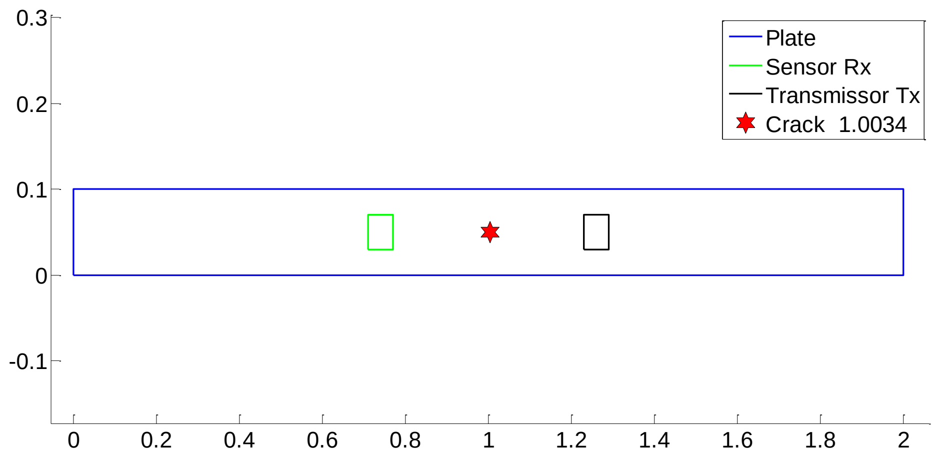

Figure 13. Location of the crack.

The location of the crack found by the approach has an absolute error of 3.4mm, and a relative error of 0.34%. It is shown that it allows to locate the defects with a high accuracy.

4.2. Two welds between the EMATs

In a CSP, the collector tubes are usually welded to a short tube anchored to the support, shown in Figure 4. This part is the most critical component of the installation because it is prone to faults such as corrosion, bad welds or leaks. It must be considered these two welds, and its effect on the received signal, for a proper inspection of CSP collector tubes. Therefore, it is crucial to correctly identify these welds find the defects in the rest of the pipe, or bad welding.

This experiment was carry out in the CSP test rig, which replicates the dimensions of a CSP, and the objective was to identify welding in the pipes with the EMAT and the Shear waves. Figure 14 shows the arrangement of the sensors and the welds in the experimental platform. The experiment was performed 10.

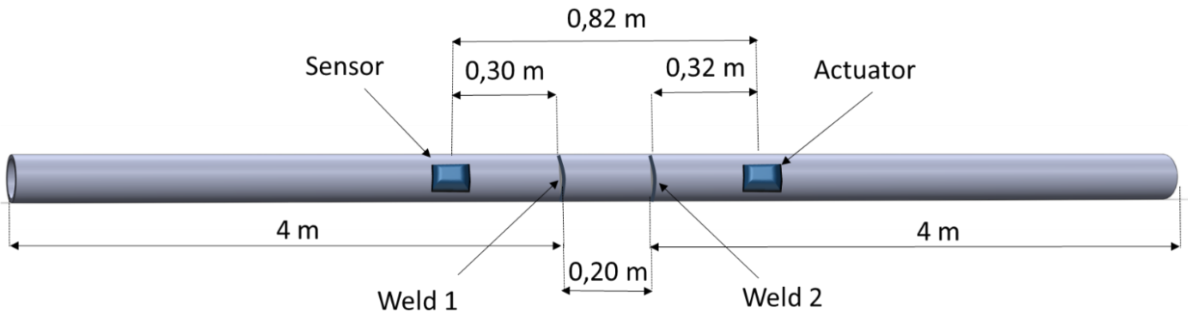

Figure 14. Welds and sensors placement in the test rig to identify welds in CSP.

The results are analyzed according to the following criteria: Crack detection and location; Two welds between the EMATs. Figure 15 presents the results considering two welds between the EMATs. It shows the edges and welds reflections by the path a.

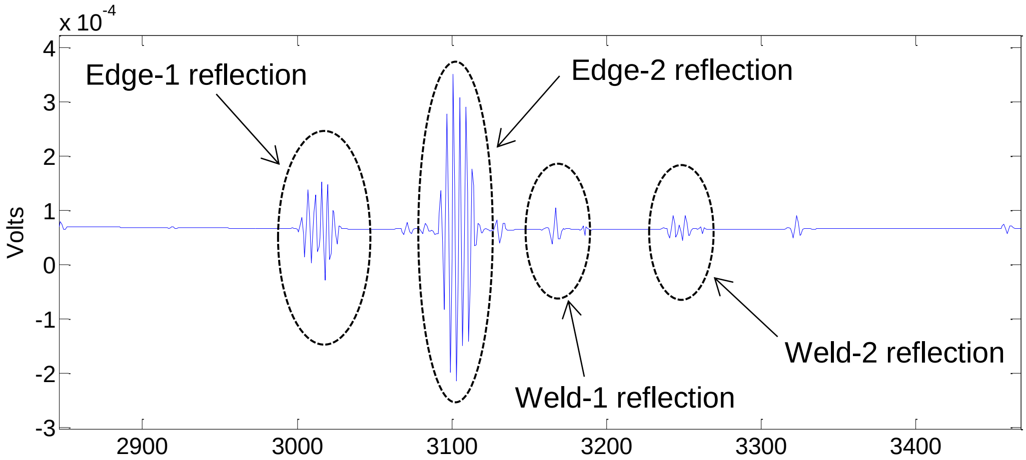

Figure 15. Edges and welds reflections.

The two welds can be perfectly identified, which allows to establish this signal as benchmark signal. If there is any element that disturbs the transmission of the ultrasonic signal, such as bad welding, the signal obtained will be different from the reference signal, shown in Figure 15, and it can be determined that there is a possible defect in that junction.

The method detects the welds. They are shown in a schema with the real dimensions of the pipe and the position of the sensors (Figure 16).

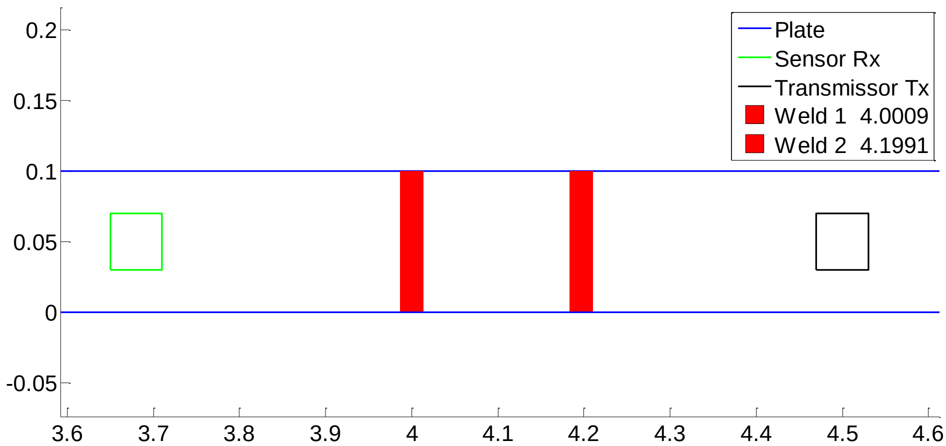

Figure 16. Welds location relative to the left edge in meters.

The absolute error for weld 1 (left side in Figure 16) is 0.9 mm, being the relative error of 0.0225%. The absolute error to locate the weld 2 (right side in Figure 16) is 0.9 mm, being the relative error is 0.02%. It shows that the accuracy of the presented method is high.

5. Conclusions

An electromagnetic acoustic transducer has been tested in a test rig designed to simulate the work condition of a concentrate solar plant. The main conclusions can be summarized as:

- The system can cover a pipe of 4 m long, and is capable of covering more than one pipe with welds.
- The method employed can detect faults and welds in the pipe performing a double validation to increase accuracy.
- A novel signal processing is used to analyses the structural health of the absorber pipes with a small error.
- The ultrasonic transducers employed in the experiments were EMATs due to their capability to work without direct contact and high temperatures.

Acknowledgements

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