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INSPECTION OF WELDING JOINTS USING ELASTOACOUSTIC SIGNALS VIA TOPOLOGICAL DERIVATIVE

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ABSTRACT

Inspection of welding joints is a must in many industrial applications to avoid defects that might lead to breaking of crucial parts. In this work, we briefly describe the inspection process, and we propose a model for defect detection based on the minimization of a cost functional by using the topological derivative. We show a numerical example to ilustrate the performance of the proposed method.

Keywords: *topological derivative, welding joint inspection, inverse problems, elastoacoustics*

1. INTRODUCTION

The inspection of welding joints is a mandatory process to ensure safety of metallic manufactured components in many industrial areas such as automotive, aeroespace or defense. Small defects, like air bubbles or slag inclusions inside the material, might result in cracking or breaking of the joint during its operation over time. As a result, robust and precise methods to ensure the safety of the welding joint are necessary. Figure 1 shows an example of a welding joint probe.

In this work we briefly describe the process of joint welding, during which, circumstancially, small air bubbles may appear. Then, we will provide some details about a current non-destructive technique used in industry for inspection of welding joints which provides data that is analyzed to determine the structural health state of the welding structure. This will be done in Section 2.

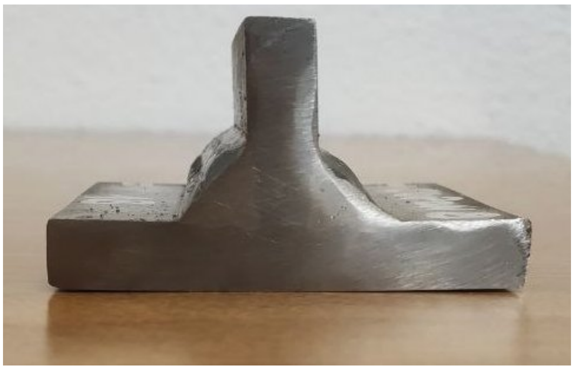

Figure 1. Welding joint probe.

Measured data will be then processed by considering a minimization problem, which is detailed in Section 3. In this paper, we propose to approach the resolution of this minimization problem by using a mathematical tool called topological derivative. This tool measures the sensitivity of a cost functional to infinitesimal domain perturbations. In our previous works [1,2], it has shown promising results in the detection of defects in welding joints using a simplified model based on acoustic waves. Other works have shown encouraging results using the topological derivative in elastic problems for thin plates [3, 4]. Given the promising results in both cases, in this work we propose an improvement in the modelization of our previous work by considering the elasticity equation instead of the model used in [1, 2], which was based on the wave equation. The definition of the topological derivative and the description of how to apply it to our particular problem will be presented in Section 4.

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Finally, in Section 5 we will show a numerical test that will serve as a proof of concept to visualize how the proposed methodology works by considering an example that mimics, considering certain simplifications, the inspection of a joint analogous to the one shown in Figure 1. In this example we will simulate a welding process during which a small air bubble has arisen inside the filler material. This paper ends with our conclusions and some comments about future work in this research line.

2. WELDING JOINTS INSPECTION PROCESS

The welding joints considered in this work have two separated regions: two pieces perpendicular to each other forming a T-shape (in dark grey colour in Figure 2) and the region with filler material (in light grey color in Figure 2). During the welding process, the two separated pieces are joined together in only one using the filler material. Our goal is to check that, during this process, no defect has been generated inside the filler material.

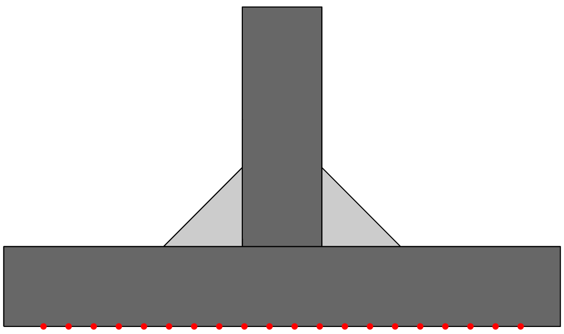

Figure 2. Welding joint regions and excitation.

For inspecting the welding joint, an array of actuators is placed at the bottom piece surface (red dots in Figure 2 represent the position of the actuators adhered to the piece). Each actuator exerts a force perpendicular to the piece surface by vibrating at a certain frequency.

In most cases, the same actuators used as emitters can be used, conversely, as sensors to measure the response of the welding joint to the vibration. These measurements correspond to the deformation field perpendicular to the surface of the piece. The measurement collected at each sensor corresponds to the signal generated by the emitter scattered by the welding joint and by the defect, if present.

3. STATEMENT OF THE DEFECT DETECTION PROBLEM

Currently, the majority of the detection methods in industry are based only on the difference between the elapsed time of the excitation and the measured signal for both pristine and damaged welding joint (see [5–7]). These methods do not take into account the physical phenomena underlying the wave propagation process. Other methods do take advantage of the physics of the wave propagation inside the material, and exploit it to obtain the influence of the defect presence in the measurements. Our method falls inside this category.

In our case, data is generated by emitters located at positions $\mathbf{x}_i$, $i = 1, \ldots, N$, where N is the number of emitters, at different excitation frequencies ω_j, $j = 1, \ldots, M$ where M is the number of excitation frequencies. For the inspection process, we generate a time-harmonic excitation from each emitter $\mathbf{x}_i$ at each frequency ω_j, and measure the received signal at each emitter position $\mathbf{x}_j \neq \mathbf{x}_i$. With this data, our goal is to find the defects D for which the expected measures given by the sensors ($m_{ij}^{k,D}$) are equal to the actual measures ($m_{ij}^{k,\text{meas}}$):

$$m_{ij}^{k,D} = m_{ij}^{k,\text{meas}} \qquad \forall i, j, k \neq i. \tag{1}$$

As it is expected that the measurements $m_{ij}^{k,\text{meas}}$ may contain errors inherent in the measuring process, obtaining a solution for the problem (1) is very demanding. In fact, this problem is a so-called ill-posed problem in the inverse problems community (see [8]). For this reason, we propose a less demanding formulation, by considering the following minimization problem: find, for each excitation source and each frequency, the defects D that minimize the following cost functional:

$$\psi_{ij}(\Omega \setminus D) = \frac{1}{2} \sum_{k=1,\, k\neq i}^{N} (m_{ij}^{k,D} - m_{ij}^{k,\text{meas}})^2 \tag{2}$$

where Ω is the welding joint domain.

4. TOPOLOGICAL DERIVATIVE

The topological derivative of a given cost functional $\psi(\Omega)$ is a function that measures the sensitivity of ψ produced by an infinitesimal perturbation at each point $\mathbf{x} \in \Omega$. It can be defined as the scalar function $\mathcal{D}(\mathbf{x})$ that appears in the first order term of the asymptotic expansion of the cost functional at the perturbed domain [9, 10]:

$$\psi(\Omega \setminus B_\tau(\mathbf{x})) = \psi(\Omega) + f(\tau)\mathcal{D}(\mathbf{x}) + o(f(\tau)) \text{ as } \tau \to 0 \quad (3)$$

where $B_\tau(\mathbf{x})$ is a ball of radius τ located at $\mathbf{x}$, and $f(\tau)$ is a strictly positive monotonically increasing function that tends to zero as $\tau \to 0$. In our case, f is the measure of the ball, i.e. $f(\tau) = \pi\tau^2$. Therefore, it can be observed that:

$$f(\tau)\mathcal{D}(\mathbf{x}) < 0 \Rightarrow \psi(\Omega \setminus B_\tau(\mathbf{x})) < \psi(\Omega). \quad (4)$$

The inequality (4) indicates that, as $f(\tau)$ is a strictly-positive term, the points where the topological derivative attain the larger negative values are the points that are expected to minimize the most the cost functional. Therefore, they can be considered as damaged regions inside the material.

In our application, data come from multiple excitation sources and frequencies, and, as a result, we would consider a cost functional ψ that is a linear combination of the cost functionals ψ_{ij} defined in (2), i.e.:

$$\psi = \sum_{j=1}^{M}\sum_{i=1}^{N} \alpha_{ij}\psi_{ij} \quad (5)$$

where $\alpha_{ij} > 0$ are weights to be selected. By linearity, the topological derivative of the cost functional (5) is a linear combination of the topological derivative for each excitation and each frequency:

$$\mathcal{D}(\mathbf{x}) = \sum_{j=1}^{M}\sum_{i=1}^{N} \alpha_{ij}\mathcal{D}_{ij}(\mathbf{x}) \qquad \mathbf{x} \in \Omega_{\text{insp}} \quad (6)$$

where Ω_{insp} is the inspection area, which in our case corresponds to the filler material zones (in light grey color in Figure 2). Previous works [4, 11] propose normalizing the contribution of each experiment by defining the weights using the following expression:

$$\alpha_{ij} = \frac{1}{|\min_{\mathbf{y}\in\Omega_{\text{insp}}}(\mathcal{D}_{ij}(\mathbf{y}))|}. \quad (7)$$

This expression ensures that each of the terms in (6) verifies that $\min(\alpha_{ij}\mathcal{D}_{ij}) = -1$. Insipired by this idea, in this work we propose a slightly different normalization, where we take:

$$\alpha_{ij} = \frac{1}{\max_{\mathbf{y}\in\Omega_{\text{insp}}}(|\mathcal{D}_{ij}(\mathbf{y})|)}. \quad (8)$$

which is used to ponderate each individual contribution in an analogous manner, but provides better results than the normalization proposed in (7).

5. NUMERICAL EXAMPLE

In this work we test our method in a configuration that resembles the welding joint probe illustrated in Figure 1. Since no experimental data is available, we consider numerically generated data to validate our model and check its potential use for defect detection. More detailed cases and studies concering the influence of different parameters in the detection process will appear in [12].

We consider a welding joint consisting of two steel pieces of 10 mm of thickness perpendicular to each other, where the horizontal piece is 70 mm long and the verical one is 30 mm long, forming the shape that can be observed in Figure 2. We consider that, during the welding process, an air bubble, which is the most common type of defect in welding processes, has been generated. In our example, an air bubble of 1 mm of diameter has been generated inside the right-hand welding seam, as can be observed schematically in Figure 3.

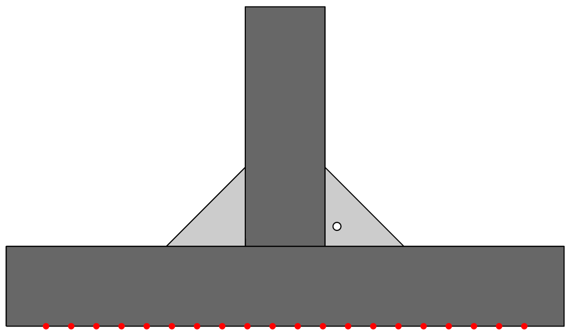

Figure 3. Example of the defect case considered

As our goal is to detect damages generated during the welding process, we will only evalute the topological derivative indicator function (6) in the area corresponding to the welding seam (light grey areas in Figure 3), as we assume that the steel pieces have been previously inspected and are defect free.

For generating the elastoacoustic waves we consider 20 emitters (red dots in Figure 3) exciting at 40 different frequencies in the range between 0.1 to 1 MHz. The material considered is carbon steel S355J, a metal commonly used in different engineering areas.

Numerically generated data has been poluted with up to 10% random white noise in order to simulate the unavoidable measurement errors present in experimental testing. For this data, the values given by the topological derivative defined in (6) are shown in Figure 4. Recall that points where the largest negative values are attained will be identified as belonging to damaged areas, i.e., this function will be used as a damage indicator function.

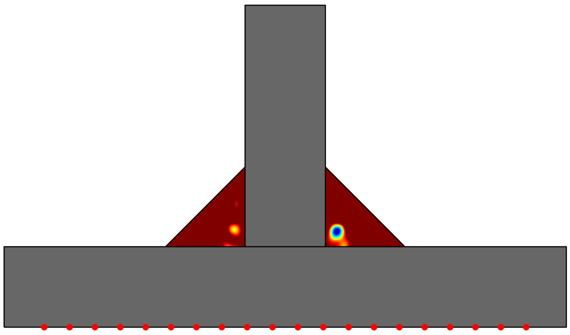

Figure 4. Topological derivative indicator function for the presented case (blue colors represent the points where the indicator attains the largest negative values, i.e., the points selected as belonging to damaged areas).

Comparing Figure 3 and Figure 4, it can be observed that the zone identified as damaged (represented with blue colors in Figure 4) is close to the real zone where the air bubble is actually located (which corresponds to the small white circle in Figure 3).

6. CONCLUSIONS AND FUTURE WORK

We have presented a preliminary test where the use of the topological derivative for damage detection inside welding joints using elastoacoustic waves shows promising results, as it is able to detect a small air bubble with good precision. As already stated in the literature for many applications, dealing from defect detection in acoustics, electromagnetism, tomography, etc., we have observed that the topological derivative is a robust method, capable of detecting defects even in cases where high levels of noise are present.

Given the promising results, currently we are working in developing more accurate models such as a three-dimensional model, multimaterial models or different type of welding joint shapes. Also, we are in process of obtaining experimental data for validation of the method with real data. Further details will appear in [12].

7. ACKNOWLEDGMENTS

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