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AN EXPERIMENTAL APPROACH FOR CRACK IDENTIFICATION/ASSESSMENT IN PIEZOELECTRIC MATERIALS

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Abstract. *In this work, an experimental approach for the identification of through thickness cracks in piezoelectric materials is presented, where the electric potential on the surface of the PZT elements was measured at different locations before and after the crack was introduced. A damage index (DI) was defined, based on the amount of change in electrical potential between the intact and damaged states, which was later used to develop an algorithm for identifying and assessing cracks in a PZT element under a time harmonic load. Cracks of different lengths, depths and orientation were successfully identified.*

Keywords: *PZT, Electric potential, Cracks, Damage identification.*

1. INTRODUCTION

Piezoelectricity is the phenomenon described as an electric field is generated upon applying a mechanical load and vice versa. This effect is utilized for the development of piezoelectric sensors and actuators. Piezoelectric wafer active sensors (PWAS) are relatively cheap and make use of the piezoelectric principles. For many years, PWAS was used in structural health monitoring (SHM) for generation of guided waves which have high sensitivity to surface and embedded structural damage. They have been widely used to develop various damage identification algorithms for assessing delamination, de-bonding, holes, cracks/notches and corrosion in both composite and metallic materials [2, 3, 7, 11, 12, 14].

The behavior of the piezoelectric materials (e.g. PZT) has been studied extensively in the past decades. Researchers have focused on the study of the effect of damage on the measured dynamic response of structures where PZT elements were used as actuators or sensors. However, limited attention has been directed towards monitoring the state of the PZT elements themselves, which is considered very critical in order to ensure that the acquired data host structure are trustful.

PZT sensors are usually brittle and could easily crack, several reports indicated that a positive electrical field applied to the PZT ceramic could slow down the crack propagation, however a negative electrical field would have an contrary effect [9, 13, 16]. Putting a structural component in service with the piezoelectric ceramics installed on it, entails the need for evaluation methods to access the integrity of the structural health monitoring system itself during the life service. A minimum amount of work have focused on inspection of the sensors, while some researchers have focused on numerically simulation the change in electric potential due to the existence of crack or damage [4, 8, 10], on the other hand no experimental results has been recalled.

In this work, PZT ceramics with different types of damage including through thickness cracks and holes were assessed experimentally. Measures of the electric potential are taken at different locations on the PZT surface and compared to the original state. A damage index is defined and a hybrid scheme is proposed, using probabilistic analysis, sensing paths and mapping of the damage indexes.

2. Experiment

2.1. Sample preparation and experimental set-up

Two PZT plate measuring 50 x 50 mm (PQYY+0598) with a thickness of 1mm were bonded to an aluminum plate (60 x 60 mm acting like a substrate) using LOCTITE© super glue. The properties of the PZT ceramic are shown in Table 1 [1]. Another circular PZT element measuring 10 mm in diameter and 1 mm in thickness was placed on the opposite side of the aluminum plate and located in the middle of the plate as shown in Fig. 1 functioning as actuator.

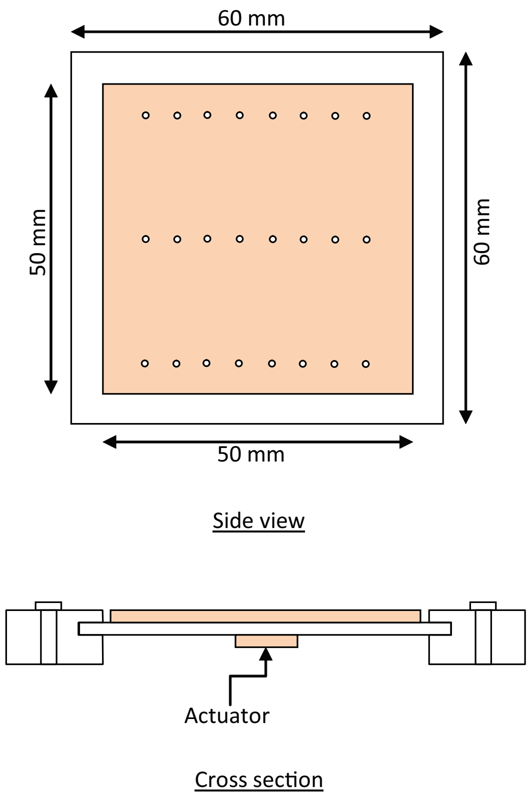

Figure 1. Schematic view of the experiment set-up.

Table 1. Piezoelectric plate properties.

Physical and dielectric properties		PIC 151	Unit	Value
Density		ρ	Kg/m^3	7800
Curie temperature		T_c	$^\circ C$	250
Relative permittivity	In the polarization direction	$\epsilon_{33}^T/\epsilon_0$	-	2400
	Direction $\perp$ to the polarity	$\epsilon_{11}^T/\epsilon_0$	-	1980
Electro-mechanical properties				
Coupling factor		K_p	-	0.62
		K_t	-	0.53
		K_{31}	-	0.38
		K_{33}	-	0.69
Piezoelectric voltage coefficient		d_{31}	$10^{-12}C/N$	-210
		d_{33}		500
Piezoelectric voltage coefficient		g_{31}	$10^{-3}Vm/N$	-11.5
		g_{33}	-	22

A sinusoidal tone burst enclosed in a Hanning window with peak-to-peak voltage of 15 Volts was used as the input signal for the actuator. Activation and acquisition of wave signals were fulfilled using an active signal generation and data acquisition system developed on the VXI platform, consisting mainly of a signal generation unit (Agilent© E1441), signal amplifier (PiezoSys® EPA-104), signal conditioner (Agilent© E3242A) and signal digitizer (Agilent© E1437A). The wave signals were captured at a sampling rate of 20.48 MHz. The acquisition duration was set to insure that the activated wave modes were captured. Three damage cases were introduced into the ceramic plate and they are summarized in Fig. 2. The panels were clamped at the four edges during the experiment. Twenty four measurements of the electrical potential were taken on top of the plate as show in Fig. 2.

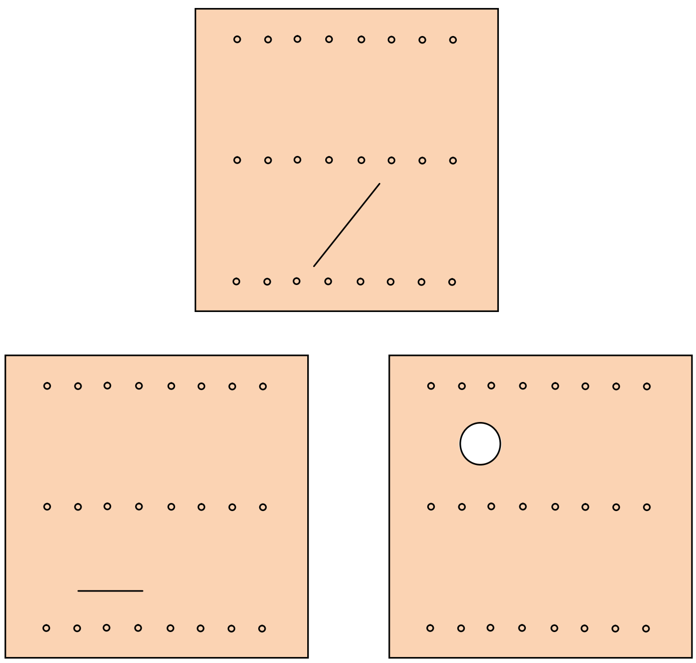

Figure 2. Damage cases tested.

The objective of this set-up is to determine the influence of different types of damage on the measure of the electric potential. It may be seen that is straight forward to detect damage in a PZT plate, however is slightly difficult to quantify it accordingly.

3. Signal processing and data fusion

The applied methodology for damage identification in piezoelectric materials was to define a damage index (DI) as the quantification of the damage influence on the acquired signal. The DI was calculated using the correlation between two different states, i.e. the damaged and the undamaged, and it is stated as

$$\rho_{x,y} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{\left(n\sum x_i^2 - (\sum x_i)^2\right)\left(n\sum y_i^2 - (\sum y_i)^2\right)}} \tag{1}$$

where $\mathbf{x}$ and $\mathbf{y}$ are two signals with n entries. Low values of the correlation indicates that the damage is very close to the point of inspection, in contrast, high values means that the damage is far away.

Data fusion is applied to obtain an approximation of the area affected by the damage. This scheme has the advantage of providing a graphical solution in the considered domain. A number of sensing paths D_{sk} is considered, taken from the known measuring points S_m ($m = 1 \cdots 24$) to a specific position (x, y) on the plate. The probability of the presence of damage (POD) can be defined as [15]

$$P(x,y) = \sum_{k=1}^{M} DI_k W_k \tag{2}$$

where M is the number of measurements, $DI_k = 1 - |\rho_{x,y}|$ is the damage index and W_k is a weight parameters which depends on the distance between position (x, y) and the kth measuring point. In this work, a Gaussian distribution was used in order to smooth the distribution of the damage index. The parameter W_k can be written as

$$W_k = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{D_{sk}^2}{2\sigma^2}\right) \tag{3}$$

with the standard deviation parameter $\sigma = 12$ mm.

4. Results

A 5-cycles toneburst wave at the centered frequency of 200 kHz was used as exciting signal, except if specified differently. The current response corresponds to the actual damage state of the PZT plate, and it is compared to a reference state, composed by the measures of the previous state. Damages were introduced into the PZT plate and their assessment will be presented in the following sections.

4.1. Slanted crack identification

A slanted crack centered at the position (25.95;14.5) mm with length 21.58 mm and orientation $\theta = 56.5°$ is analysed. Due to the particularity of the material properties, the results are very similar at all measuring positions. The measured signals in Fig. 3 represent the comparison of the present and reference state at the position (27.65;25.0) mm.

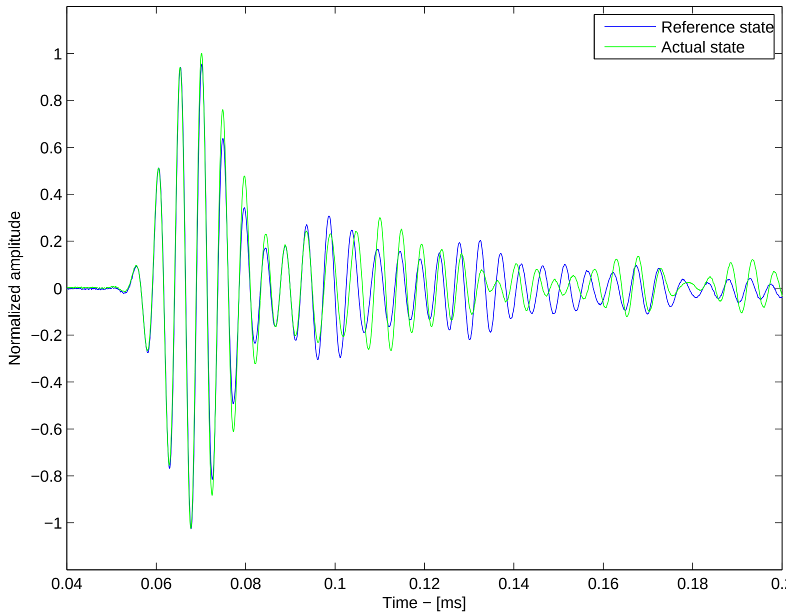

Figure 3. Comparation between present (damaged) and reference (undamaged) states.

The difference in the amplitude of signals is clearly identified, and in addition the crack resulted in some time delay between both states. It may be challenging to extract the damage features from the signals in order to located and assess the damage.

As stated before, the damage index depends on the correlation of the signals from different states. High values indicate a significant difference of both signals, whilst small values implicate that the signals are very identical to each other. Fig. 4 includes the data fusion of the probability image of the damage, calculated using Eq. (2), where the DI is obtained from the present and reference states. The data fusion of the results in this damage cases did not give precise prediction of the crack location, which may be attributed to two factors: (a) the signal obtained from the damage state is very identical to the reference one, and (b) the actuator is fixed at the center of the plate, therefore it may restrict the damage sensitivity provided by the input signal.

An alternative was to map the current DI into a new configuration, where the information concerning the state of the plate is the same, and still allowing the data fusion to present relevant information of the probability of damage in the plate. This approach is very common in damage identification problems using neural networks [5]. In this situation, a large amount of data representing the analysed problem is normalized in function of a mapping technique, leading to a faster training of the neural network and improved identification results. For more details refer to [4, 6, 12].

A Gaussian type mapping was applied and it is defined as

$$\mathbf{z} = (\mathbf{x} - \overline{x}) \left(\frac{z_\sigma}{x_\sigma} \right) + \overline{z} \tag{4}$$

where $\overline{x}$ and x_σ are the mean and standard deviation of $\mathbf{x}$, respectively. $\overline{z}$ and z_σ are the

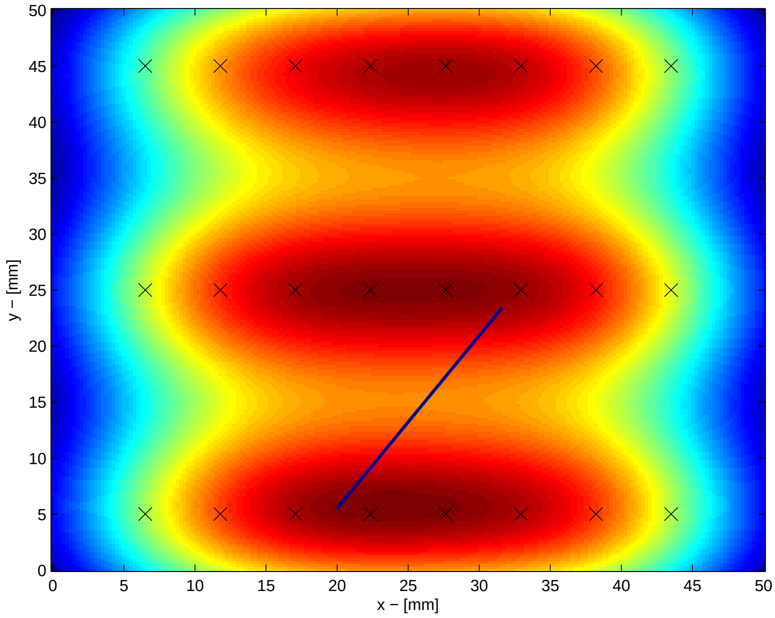

Figure 4. Data fusion of present (damaged) and reference (undamaged) states for the slanted crack identification.

desired values of mean and standard deviation of the resulting mapping. In this study, $\overline{z} = 0.5$ and $z_\sigma = 1$. The application of this mapping technique is consistent with the calculation of previous parameters for obtaining the POD of the plate, since the weights have a Gaussian distribution as well. Fig. 5 shows the new reconstructed image after the mapping of the DI.

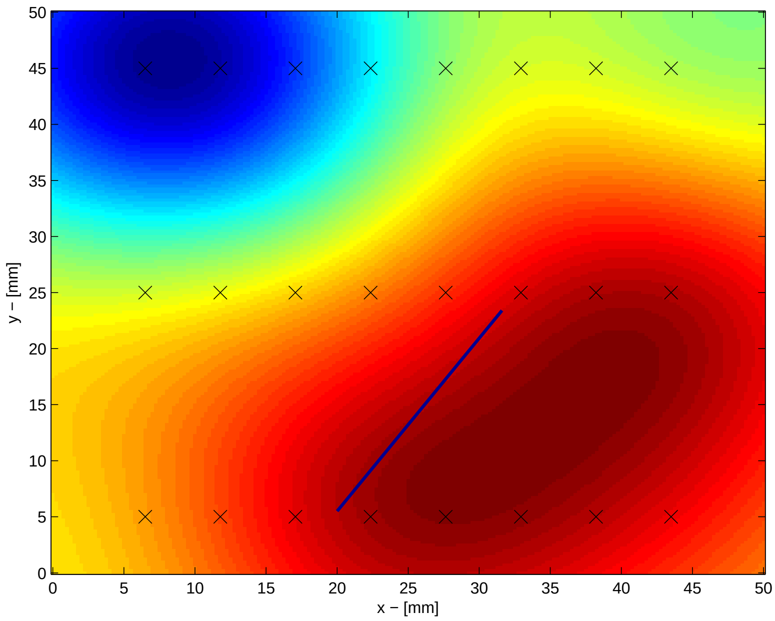

Figure 5. Data fusion and mapping techniques applied in the slanted crack identification.

The crosses indicate the signal acquisition positions and the line depicts the real crack. A dramatic improvement in the results was noticed upon introducing the mapping into the algorithm.

4.2. Horizontal crack identification

Another crack with zero slope was introduced into a second plate and was evaluated. The crack is centered at the position $(15.5; 10.1)$ mm with length 8 mm and parallel to the x-axis. Fig. 6 shows the signals of present and reference states. In this case, the excitation signal is centered at the frequency 250 kHz. As in the previous case, only the signals at one position are shown for demonstration.

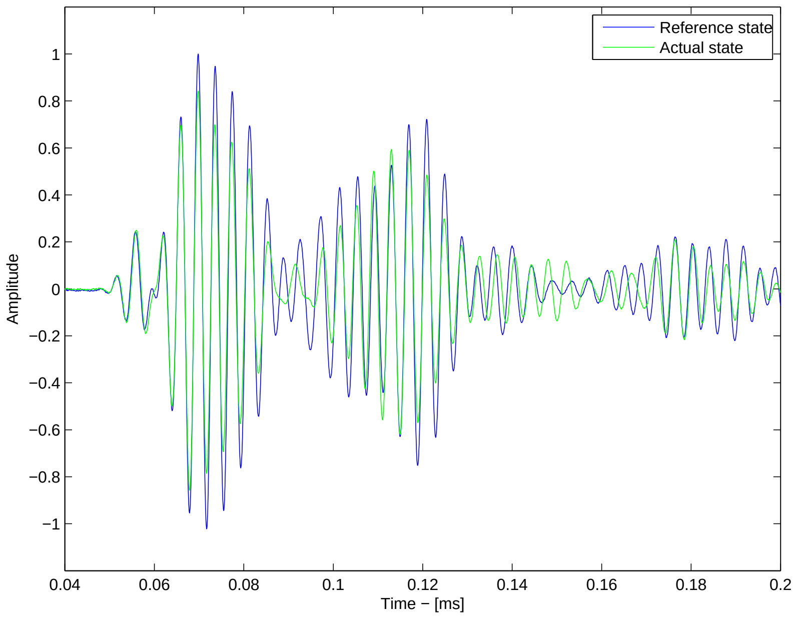

Figure 6. Comparation between present (damaged) and reference (undamaged) states for the horizontal crack identification.

A small vertical shift and the decrease of the signal amplitude in some peaks are the perceived changes caused by the introduction of the crack. Fig. 7 illustrates the data fusion of the DI mapping for the crack identification. A reasonable identification is provided for this crack.

4.3. Experimental hole identification

A hole was introduced into the PZT plate, centered at the position $(14.43; 37.5)$ mm and radius equal to 4.5 mm. Fig. 8 illustrates the signals for present and reference states. We consider the reference state as the damaged state of the previous section. Thus, the differences between the signals remarked at the present state are caused by the introduction of an additional defect in the PZT plate.

Fig. 9 depicts the data fusion of the mapped DI. An excellent estimation of the hole position was predicted.

5. Conclusions

In this work, an experimental approach for damage assessment in piezoelectric plates has been proposed, based on the correlation at several positions on the plate surface. A data fu-

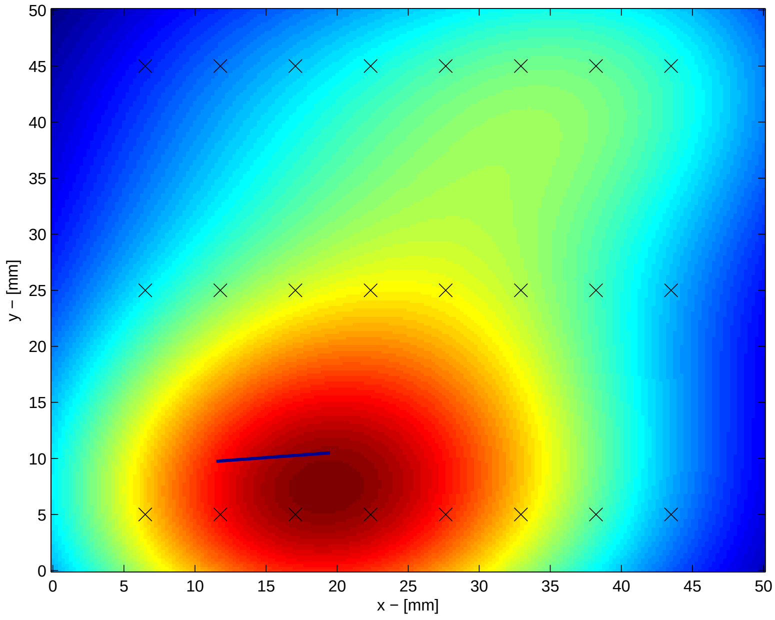

Figure 7. Data fusion and mapping techniques applied in the horizontal crack identification.

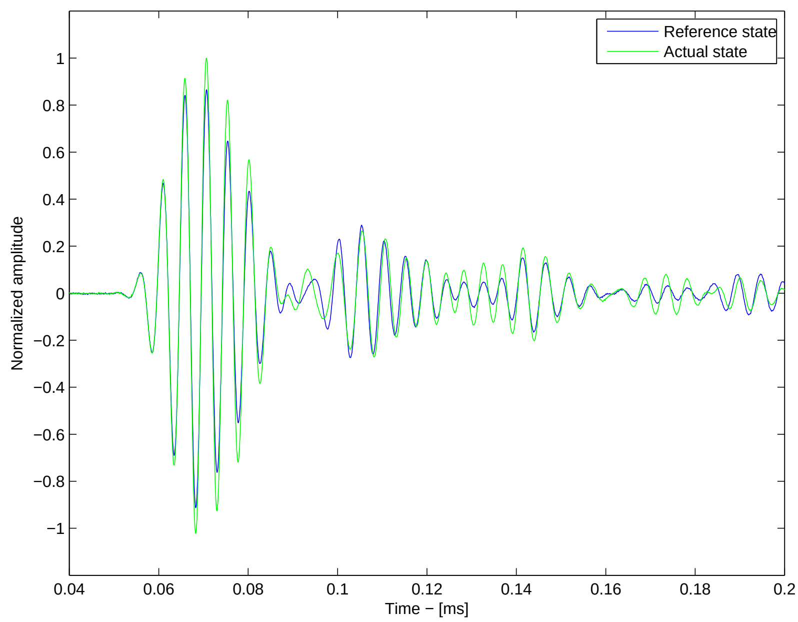

Figure 8. Comparation between present (introduction of hole) and reference (horizontal crack) states for the hole identification.

sion scheme to calculate the probability of damage over the surface, improved by the adoption of a Gaussian mapping. Changes in the electric potential were found to be very small, even for large imposed damages, which could be due to the fact that the electric potential on the surface is almost constant, since the poling direction is in the z-axis. If the poling were in the x or y-axis, a more proeminent change would be noticed. Using the proposed methodology, other types of defects such as de-bonding and impact damage can be detected and quantified.

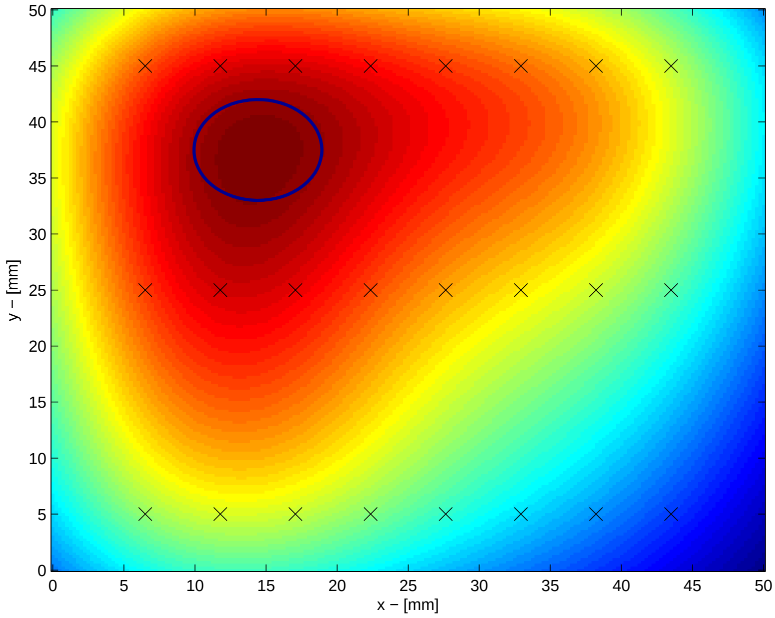

Figure 9. Data fusion and mapping techniques applied in the hole identification.

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