Inspecting Power Network Analysis on Eddy Current Test of SMAW Joints

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Abstract. Eddy Current Test (ECT) is proven to be the most reliable non-destructive assessment for electrically conductive materials. This assessment works based on the emerging Eddy Current when an alternating current is induced into conductive materials. The ECT system consists of three elements, i.e. current injection, the pick-up, and the conductive target. This system is then treated as an altered wireless power network between aforementioned elements. The use of alternating current (A/C) in this network provides a wide variety of power spectra for various analysis techniques. This paper introduces novel technique of subsurface crack assessment on SMAW welded joint of stainless steel 316 L by applying network altered response to ECT system. The analysis of the network is done by constructing mathematical models of the frequency domain in each component in the network to achieve the gain of the system. The mathematical model was constructed either for the defectless and the defected speciments, and then both result was compared to investigate and extract the information about the crack. The experiment also performed to confirm the simulation from the modeling. The experiment succeeded to differentiate the size of the subsurface crack on certain working frequencies.

Keywords: Power network, Eddy Current, welded joints, decomposition, transfer function, response

1 Introduction

Eddy current is the form of electromagnetic current that emerges caused by the presence of alternating magnetic fields when electromagnetic current injected to electric conductive materials. Since crack were defined as the presence of air or vacuum inside the metallic dense material or we might mention it as the discontinuities, and as the air had different electric permeabilty compared to the dense metallic substance surrounding it, the presence of air or discontinuities can be detected if we inject the metallic substance with electric currents by inspecting the difference of magnetic flux produced by the dense and the one with discontinuities in it [1]. This phenomenon was utilized with successful results on assessing various conductive of materials for decades. To be more specific, this technique of assessment is done by measuring and the compares the difference between the input of injected electric current and the output electric current on feromagnetic metal after the induced electric current passing through the speciment or the target of interest.

The Eddy current test system consists of three main elements, i.e. the source of signal, the target, and the pick-up system which were consists of display system, which displaying the result of the measurement [2]. The source signal, is delivered to the driving coils which is physically takes the form of helical or flat planar coils, and the signal were then injected to the conductive feromagnetic target where the target will alter the injected signal caused by the reflection and dissipation of the target and the remaining of the flux were picked up by pick-up coils to be measured. The rest of the remaining signal that detected by the pick-up system were termed as Eddy Current and this is where the terms of Eddy Current Test (ECT) came from. ECT also sometimes called the Magnetic Flux Leakage (MFL) since the spectra of signal to be measured were the magnetic flux produced by the injection of electromagnetic current.

The sensitivity of detection coils and the excitation signal plays important roles to success measuring result. Effective penetration depth dan sensitivity of detection system can be achieved by applying wide frequency range in induction signal [3]. Most of the works in ECT were subjected to probe design optimization to assess various metallic targets [4]. The developing technology of manufacturing technique i.e 3D printing technology also employs ECT to assess the integrity of 3D printing products by implanting feromagnetic metallic substance to the 3D printing product, so it assessible by ECT [5]. In assessing welded joints, the success of ECT non-destructive test methods were successful as in the assessment on other conductive metal and so does the researches subject of the SMAW welded joints assessment by ECT technique [6].

In this paper, we use novel technique to assess the crack on the conductive material i.e SMAW welded joints using ECT technique system that consists of Function Generator to inject the electric current through driving coil and a DSO Oscilloscope which connected to the pickup coil to display the results of signal produced after passes the target. Both of driving coils and pick-up coils were helix. The signal acquired and recorded from the DSO oscilloscope then being collected and these becomes the datas that needs to be processed. The arranged test system then treated as the network of wireless power transfer system that as forementioned consists of driving coils, pickup coils and the target. Then the network response system is modeled is constructed to acquire the systems responses due to injected input signal. The system response is then analyzed to yield the transfer function of the system. The transfer function is defined as the gain or the ratio of output spectra, which in this experiment we use the rasio of output frequency to the injected frequency. The working frequency of the system were function of several parameters i.e. permeability, conductivity, and geometry. This novel technique will extract more comprehensive and rapid information about crack that resides in the dense conductive materials. To be more robust about investigation of the crack, conventional impedance technique also performed to compare the results of proposed technique to the conventional technique which only process the results of measured impedance [7],[8]. The network response modeling in this works offers analysis of output and input spectra by separating the network of ECT system into three distinct parts so it allows separate modeling of each components of the system. The models then can be represented into elements of algebra to obtain the total representation of the whole system.

When the total representation of the systems acquired, Linear Time Invariant (LTI) premises is applicable to the network system for further process. LTI will provide the relationship between injected signal as the input and the response that gained from the ECT network parameter (driving frequency, mutual coupling or power interaction of the three) which were carries more rich information about the network. From aforementioned description, the objective of this research is to assess the crack detection in ECT by applying frequency response analysis on wireless power transfer (WPT) of ECT.

2 Decomposition of the altered frequency network response

Magnetic induction works based on the effect of Electromagnetic (EM) field. The far or near field, depends on the length of waveforms, which is when it is smaller than one wave length, it classified to near field, and if it is longer than one wave length it classified as far field [9]. Authors also classified power transfer magnetic induction into coupling and radiative, which were the coupling classified to magnetic field and electric field, and the radiative type classified into microwave and laser [10]. The ECT can be classified into near field wave, since the physical distance of the coils to the targets were shorter than the wave length in the transmission process.

The ECT network system are consists of driving coil, pick-up coil and a target specimen which is made of conductive material. ECT performed by injecting A/C currents to the target through driving coils in the excitation coil system, and then pick-up coil picked-up the signal emitted from the target after the signals being dissipated and reflected from the target [11]. This test wont work on DC signal, since it requires fluctuative signals which is only provided by A/C signals. One of the advantages of A/C currents usage as the injection signal to ECT system was that A/C signal provides possibilities of wide variety spectra for various analysis techniques. Besides, A/C current offers more sensitive detection due its alternating signal compared to the use of DC current, so in order to perform success power network interaction, fluctuative magnetic field is required which mean that the network of ECT had to operate in A/C [12]. Since the injected signal will interactively works in the ECT system i.e. driving and pick-up coils and the target, this ECT system can be considered as a network of wireless power interaction. From this definition, there will be several mutual induction occurs between the three members of the system.

ECT works by comparing the input signal to the output signals of defect area and non defect area, so we can also use the ratio of output to the input signals to distinct defectless area and the area with crack or defect. In control engineering, the respons of a system to disturbance applied on the system, called the system response. The ratio between the input signals and the output signal measured from the time domain to frequency domain is called the transfer function. Generally, the transfer function models can be constructed by the mesh technique which is superposing the results of individual mesh to obtain the response of the whole system, or response of a certain or particular mesh in the system. In this work the mesh of interest is the mesh at the pick-up system. The pick up system had the information of response of the whole system of ECT. Since the models of the response actually the response of the whole ECT system, and we only need to obtain the response of the pick-up system, we need to decompose the obtained comprehensive model into the mesh of interest i.e. the pick-up system. The altered frequency in this works relates to the working voltage which is injected to the target from the driving coil. By applying time responses and frequency analysis to the power network the location and the volume of crack geometry is possible to be determine. Since the target with defect yield different responses to the excitation signal, the existence of the defect will be easily known. Another consideration on this proposed assessment technique is that the transfer function is merely the ratio of output to the input signals [12], so the ECT based on network response system assessment can yield more rapid results with more information about the size of the crack.

The modeling of the ECT system can be construct as the response of three components (driving coil, pick-up coil and conductive target specimen), so we can model the transfer function of the ECT system in the time and frequency domain for the derivation of network response mathematical model for analysis as shown in Figure. 1. (a) and (b):

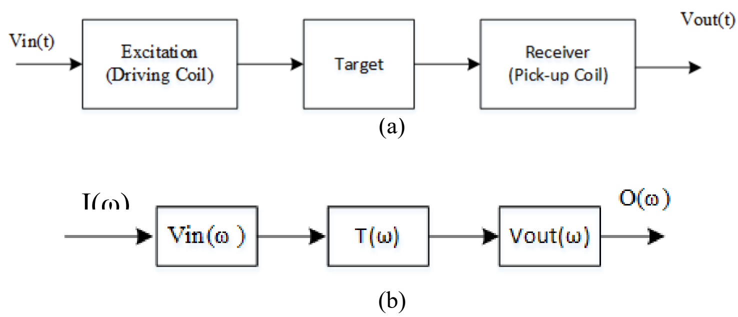

Fig 1. (a) The time domain and (b) frequency domain modeling

From the depiction above in Figure 1, the ECT system is a network system of impedance where $s = j\omega$ and ω is the angular frequency of the system. From there we can write the transfer system of the impedance of ECT network system as:

$$T(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} \quad (1)$$

From equation (1) we can see that the response of the system to input or we can say the gain is the response of the ECT system. The target will dissipate and reflect the signal injected to it, or we can say that the signal is processed in the target in such ways so the signal from the target to the pick-up system alters to a certain level. If $V_{in}(\omega)$ is the excitation voltage through driving coils, $V_{out}(\omega)$ is the voltage delivered to the pick-up coil from the target T(ω) where all the injected flux from the driving coil processes in such ways so the presence of the target must be counted as another structure in the network power transmission between the driving and pick-up coils. Since the target is conductive materials, so it poses inductive and impedance properties that will interfere the power network transmission between coils. The presence of crack in the target will further alter the impedance of the target since cracks is physically the forms of discontinuities inside dense conductive media or the existence of air or vacuum in the dense material [13]. So the presence of the third system in the network must taken into account [14]. The schematic illustration of the network power coupling and interaction between conductive targets, driving, and pick-up coils is depicted in Figure 2.(a). The equivalent circuit with controlled power source from the driving coil to the target and the pick-up coils is shown in Figure 2.(b). In the equivalent circuit, the conductive target is expressed by the induction equivalent considering it as an inductive element with all its impedance properties. The induction network of power transfer interaction between the coils (driving and pick-up coil) through the target can be replaced by the mutual induction L12 and the interfere to the power network caused by the target to either driving and pickup coil denoted as M_{DP}. Subscript T on L, R, and I is the induction, resistance, and the current in the target. By combining the third system or target to the network with all the mutual induction equals in the system (M_{DP} and L_{12}), the mathematical models of the system can be easily constructed.

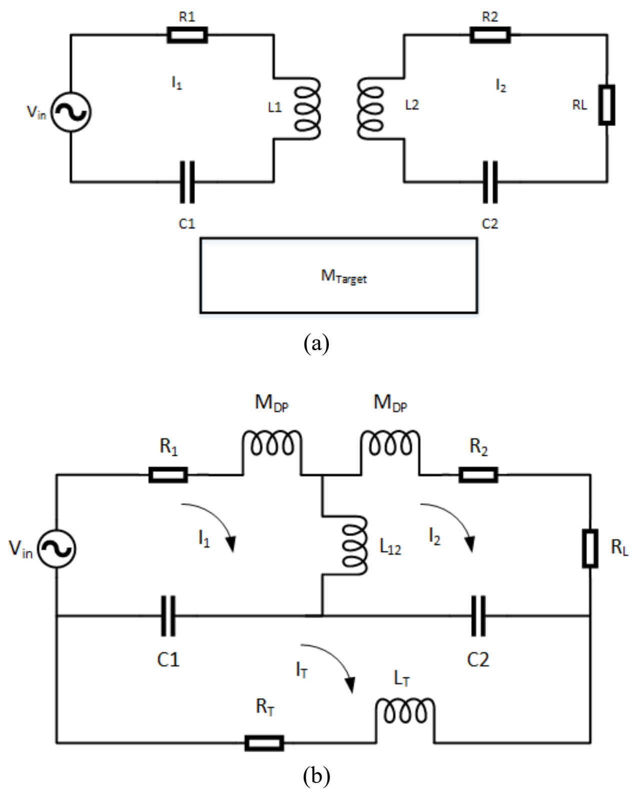

Fig. 2. (a) The network coupling of power between the driving coils, pick-up coils and conductive target, and (b) the equivalent circuit of the network

By applying theory of Kirchoff Voltage Law (KVL) to equivalent circuit diagram in Figure 2. (b) which state that in any closed loop network the total voltage on the loop is equal to sum of all the voltage drops within the same loop, we can construct the mathematical model of the response in ECT system network of the three network elements by circuit theory:

$$
\begin{aligned}
V_{in} &= (R_1 + j\omega M_{DP})\, I_1 - j\omega L_{12} I_2 - \tfrac{1}{j\omega C_1} I_T \\
0 &= -j\omega L_{12}\, I_1 + \left(j\omega M_{DP} + R_2 + R_L + \tfrac{1}{j\omega C_2}\right) I_2 - \tfrac{1}{j\omega C_2}\, I_T \\
0 &= -\frac{1}{j\omega C_1}\, I_1 - \frac{1}{j\omega C_2}\, I_2 + \left(\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} + j\omega L_T + R_T\right) I_T
\end{aligned} \tag{2}
$$

Equation (2) is the mathematical models of the whole network system, and since the response of the interest is on the output of the target, we need to decompose the continuous system to obtain the focused response only on the pick-up section. By using Cramer's rule to decompose the simultaneous equation in equation (2), we will acquire

$$
I_T = \frac{\begin{vmatrix} R_1 + j\omega M_{DP} & -j\omega L_{12} & V_{in} \\ -L_{12}s & j\omega M_{DP} + R_2 + R_L + {}^{1}/_{j\omega C_2} & 0 \\ -\frac{1}{j\omega C_1} & \frac{1}{j\omega C_2} & 0 \end{vmatrix}}{\Delta} \tag{3}
$$

Where from equation (3):

$$
\Delta = \begin{vmatrix} R_1 + j\omega M_{DP} & -j\omega L_{12} & {}^{1}/_{j\omega C_1} \\ -j\omega L_{12} & j\omega M_{DP} + R_2 + R_L + {}^{1}/_{j\omega C_2} & {}^{1}/_{j\omega C_1} \\ -\frac{1}{j\omega C_1} & \frac{1}{j\omega C_2} & \frac{1}{j\omega C_1} + \frac{1}{C_1} + j\omega L_T + R_T \end{vmatrix} \tag{4}
$$

So if we take equation (3) and (4) to the definition of the transfer function as stated in equation (1) and since the focused response is on the pickup system that is measured on the target, then the transfer function is:

$$
T(s) = \frac{I_T(s)}{V_{in}(s)} \tag{5}
$$

And by substituting equation (3) to equation (5) we acquire the function transfer as follow:

$$
T(s) = \frac{\begin{vmatrix} R_1 + j\omega M_{DP} & -j\omega L_{12} & V_{in} \\ -j\omega L_{12} & j\omega M_{DP} + R_2 + R_L + {}^{1}/_{j\omega C_2} & 0 \\ -\frac{1}{j\omega C_1} & \frac{1}{j\omega C_2} & 0 \end{vmatrix}}{(\Delta)(V_{in})} \tag{6}
$$

In this case, the network response with the controlled source jω is the controlled voltage source of the driving coil and the output response determined by the current goes through the

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pick-up coil. I_2 is controlled from the driving coil and it depends and determined by current from driving coil I_1.

3 Experimental procedures

The experimental procedure in this research is done by adopting the TEAM problem 15 benchmark of ECT. According to this benchmark, measurement of the flaw is done by placing the center of the probe parallel to the center of the slot (simulated crack), perimeter of the probe is placed above the slot either from the left or right of the perimeter as shown in Figure 3. The data is taken from the three points i.e. the perimeter means the perimeter of the probe exactly above the perimeter of the slots, which is done from the left perimeter of the slot and the right perimeter of the slot. The third data collecting were done by placing the center of the probe base exactly in the middle of the slot. The measurement lift-off are 0 mm. The probe is circular designed, so it is capable of measuring the crack at any orientation. In practice, this means that as log as the center of the circular probe placed normal to the surface of the welded speciment and slot, it will gain the same magnitude of the measurement or regardless to probe lateral rotation.

The speciments used in this experiment is stainless steel AISI 316L plates, butt welded by SMAW method, with each plates had size of 50x50x10 mm and the size after being welded is 100x100x10 mm, or in other word, each of the speciments is made of two 50x50 mm plate with 10 mm thickness welded together. The welding processes were performed by certified welder. The dimension of the welding joint is 10 mm in width along the 100 mm joint on the speciment. The crack in the speciment were simulated by implanting EDM notch to the welded joint speciment. The notch depth is varied from 1 mm, 2 mm and 4 mm, 1 mm width across the welded joint. Before the notch implanted to the speciment, several non destructive inspection were done to assure that the speciment free of any flaw that might affect the results of the experiment (visual test, penetrant, and radiography test). The results of penetrant tests and radiography shown in Figure 4. If the forementioned test results the presence of defects, the correction is performed according to the AWS standards and then re-welded again until the defect no longer exist The speciments is then ready to be implanted with notch if there were no more defects.

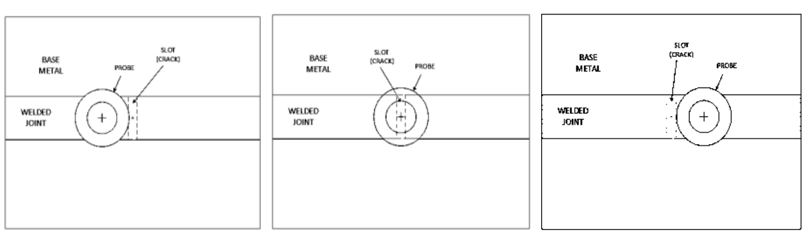

Fig. 3. Three location of the measurements

The helix coiled construction of the probe is fabricated using 0.5 mm copper wire, arranged in such way so the driving coil is placed above the detect coil. The probe is air cored and the center of the coil glued to a hollow cylindrical nylon using retinol. The probe then covered by another cylindrical nylon. Each end of the coils were connected to a pair of cables which then connected to the oscilloscope and function generator. The driving coil is

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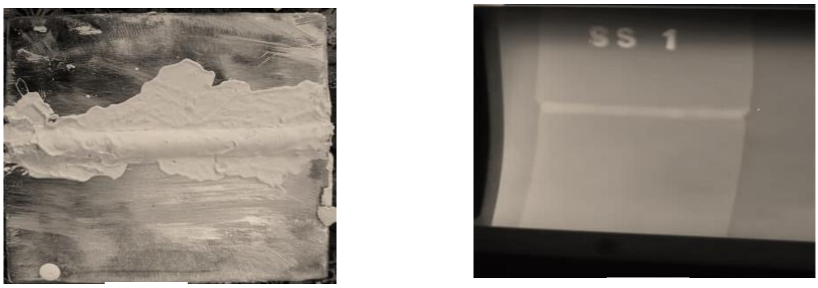
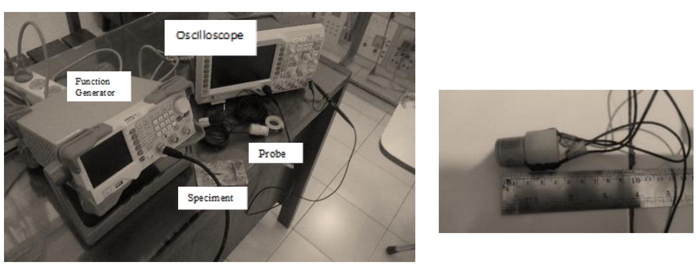
connected to the function generator and the pick-up coils connected to the DSO oscilloscope. The experimental setup and the probe to perform this experiment is shown in Figure5 (a), and the helical probe is shown in Figure 5. (b).



(a) (b)

Fig. 4. The results of (a) penetrant test and (b) radiography test

The injected signal was sinusoid and the working frequency is 120 kHz, injected voltage from 5 to 12 V. These working signal is determined by trial, in which signal is producing significant result between the defectless and cracked target until it no longer yield any change of the reading which affected by the conductivity characteristics of the probe and the target. The difference of the injected voltage from the function generator to the results on voltage reading in the oscilloscope by pick-up coil will determine the network function of power transfer and the response of the system can be calculated using control engineering theory.



(a) (b)

Fig. 5. (a) Experimental arrangement for the power network response (b) probe

To acquire successful test, beside the response of the system, the response of the probe also had to be characterized in order to determine the characteristic of the probe to the transfer and to determine its response to the input. This can be achieved by applying aperiodic signal function from the function generator to the driving probe. After the characteristic of the probe determined, the probe is then used to perform the crack detection test. Table 1. list the parameter of the experiments:

Table 1. Parameters of the experiment

Item	Unit	Value
Driving coil		
Radius	mm	22
Inductance, L_1	μH	330
Resistance	Ω	5.59
Capacitance	pF	235
Pick-up coil		
Radius	mm	24
Inductance, L_2	μH	38.7
Resistance	Ω	1.98
Capacitance	pF	235
Coils Inner Radius	mm	12
SMAW joint Inductance (M_{DP})	μH	94.1
Working frequency	kHz	120

4 Results and discussion

The mathematical modeling of the probe was constructed in order to show how the performance of the probe to test the network system and how it respond to the frequency injected through it. The response is modeled to be use with aperiodic signal, which in this case is step input and this will give the information about the gain of the probe in transient response, which mean initial to the final state, which is expected to be in steady state. From the result showed in Figure 5. it can be seen that the probe had second order response and that the probe is had good stability, which is the most important properties that a certain detecting system has to have. In other words, the probe used in this experiment will be successfully performs the test. Figure 5. also shows that the probe will cause the deviation of actual injected signal from the input source. The probe also cause damping to the ECT system that will affecting the response to the output. The probe in this experiment is sufficient and will yield satisfying result.

Figure 6. shows the result from the performed experiment. It shows that at the same working frequency, the crack of the different size in SMAW joint is successfully detected and produce different spectra level. The result also shown that at the same frequency with higher voltage to a certain quantity yield abruptly readings, so that at that state, the probe fails to work properly, which is normal and as it already expected due to the impedance of the probe as already predicted in Figure 5 about the steady state response of the probe. It also can be seen that the presence of the metal in these networking will strengthen the current due to the conductivity of the metals. The presence of welded joints even increase the injected signal up to twice its working frequency, which is 120 kHz. From Figure 6., we can see that the left and right perimeter measurement from the perimeter of the probe also produce different signal level in the measurable range caused by the variation of material conductivity in the welded joints. This conductivity properties of the welded joint alters because the process of welding that employs high heat will cause complex changes in materials properties. We also need to notice that 1 mm crack attenuate the frequency but the 2 mm implanted crack increase the frequency response caused by the self induction caused by air similar to self inductance in a coiled wire with air cores.

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Figure 7. agreed to Figure 6., where we can see that the bigger crack volume will result in higher amplitude which is and from further analysis we can conclude that the phase of the frequency difference between non defect and with the crack one will cause the shifting of phase and finally affecting the amplitude, as shown in Fig 8. We can link this phase shifting to the volume of the air inside dense target, that the more air means the bigger size of the crack and it results in different phase shifting and higher amplitude. This is possible by the presence of self induction caused by the content of air in the speciment.

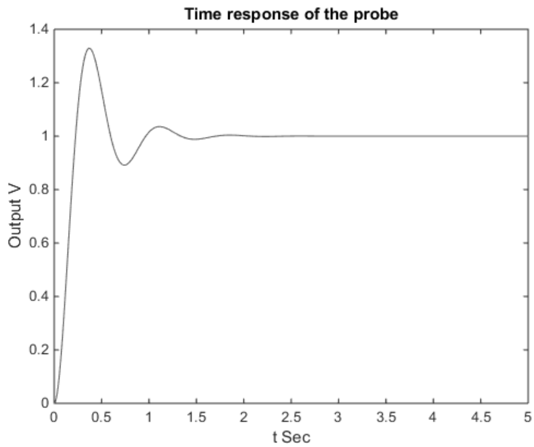

Fig. 6. The response of the probe to aperiodic signal

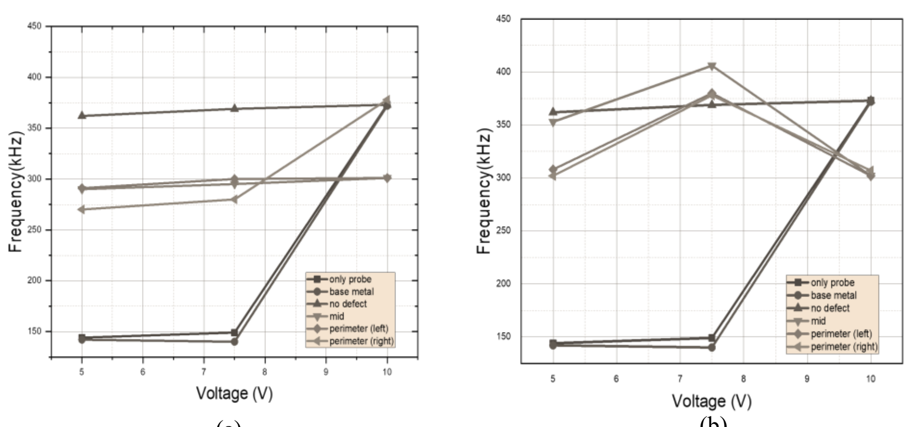

Fig. 7. The experimental results of the ECT frequency and the response on various voltage input on (a) 1 mm and (b)2 mm crack

The results also shows that welded joints causing significant escalation to the output frequency due to its high electric conductivity. The base metal lowers the output frequency as expected caused by the dissipation of Eddy Current by the base metal. The presence of crack lowers the frequency since the crack assumed to be the presence of air will alters the output frequency.

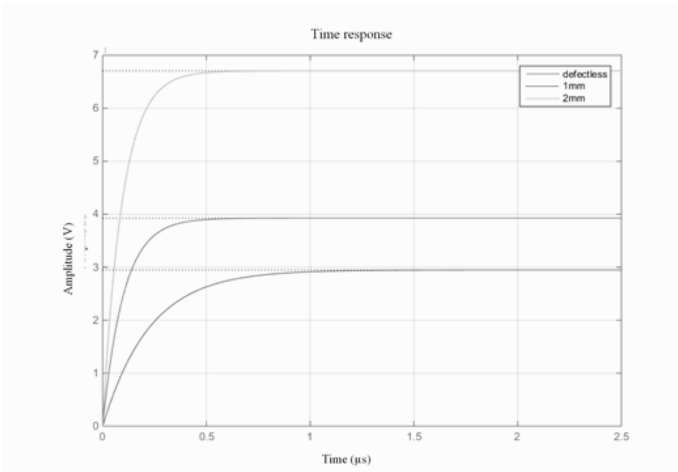

Fig. 8. Response of the network to the SMAW target as the target were defectless, contain 1mm, and 2 mm defect in the target

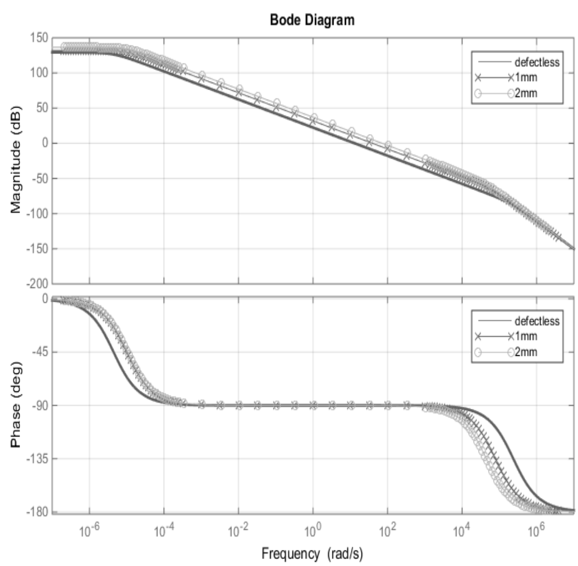

Fig. 9. The Phase-Magnitude vs frequency of defectless, 1 mm depth defect and 2 mm depth defect

From the Figure 9. we see that magnitude and gain margin shows that the network is oscillatory with good stability and it agrees to the results of the probe test in Figure. 5. Figure 8. satisfies the steady state for the three different networks analysis (defectless, 1 mm dan 2 mm) with the presence of defects and the defectless welded joint. In this case defectless welded joint attenuate the network interaction compared to the simulated defects (crack). The strengthen frequency on the network in the presence of welded joint means high gain for the same frequency might be caused by the occurrence of lag compensating that works on contrary in the network.

We also can concluded that the more volume of the defect, means the more volume of air or vacuum in the dense which also means more self inductance as other studies proves on experiments about air cored coils. In this experiment the difference between the different size of defect were more contrast compared to the previous conventional analysis technique studies. So applying transfer function technique analysis to ECT can be a tools to determine the size of the crack, which is the main challenge of ECT.

5 Conclusion

The new proposed technique for crack detection in ECT by using the network altered frequency performance to inspect the crack had performed successfully to detect the crack in the subsurface of SMAW welded joint. In this paper, the implanted crack in the subsurface with different size also has successfully differentiate by the detection system, and then by network function analysis, new technique of ECT had been established. Further studies for these novel technique required in order to determine the volume and the geometry of the flaw, since the variable of the volume of the crack can be analyzed by deriving volume to the equation of the network response. What we need to emphasized here is that the welded joint contributes significant changes in responses of the network frequency and it provide many possibilities and information about the variation of material that requires further investigation and comparison to other material identification technique.

Acknowledgements

This work was supported by Universitas Diponegoro and Universitas Muhammadiyah Semarang where the experiment was performed .

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