ICIC Express Letters
Part B: Applications
Volume **10**, Number **3**, March **2019**

ICIC International ©2019 ISSN 2185-2766
pp. **227–233**

A DESIGN AND ANALYSIS FOR WELD SEAM DETECTOR BASED ON EDDY CURRENT AND PHASE LOCK LOOP TECHNIQUE

Anucha Punapung[1,2], Noppadon Sisuk[1,2] and Anucha Kaewpoonsuk[1,2]

[1]Department of Physics
Faculty of Science
[2]Research Center for Academic Excellence in Applied Physics
Naresuan University
99 Moo 9, T. Tapho, A. Mueng, Phitsanulok 65000, Thailand
{ semiconductor; noppadon_su }@hotmail.com; anuchak@nu.ac.th

Received August 2018; accepted November 2018

Abstract. *This paper presents the design of the weld seam detector in the metal sheet using eddy current, which processes by a phase lock loop circuit. The structure of the proposed system consists of a single inductor coil which is the sensor of the system, the oscillator circuit, the phase-lock loop and non-inverting circuit. Also, the equations of eddy current testing and phase lock loop were demonstrated in this article. It can be proved the output voltage depends on the changing frequency when the detector coil found the defect in a test subject. The experiment is shown the proposed system can detect the weld seam area in the test subject. Therefore, the new techniques provide convenience and efficiency as an eddy current testing solution.*
Keywords: Eddy current testing, Phase lock loop, Weld seam detector, Nondestructive testing

1. **Introduction.** In recent year, the theft of a motor vehicle might be called auto theft. That is one of the crime issues that has increased over the years in Thailand. Often, stolen vehicles are immediately exported to aboard. However, sometimes stolen cars are disassembled, so those parts are sent to auto parts stores for selling. A conventional method is used to change a stolen vehicle to be a legally registered vehicle, which is a replacement of the stolen car chassis by the legitimate car chassis. In addition, the recovered stolen vehicles are painted to hide the weld seam by spray paint over the metal sheet. A traditional technique to check the weld seam of the chassis is using a chemical that can damage the color of the chassis. Thus, this research is proposed to combine two techniques for detecting hidden weld seam in case of stolen vehicles. The first technique is one of nondestructive testing which is called eddy current testing. The eddy current testing is a crucial inspection technique of nondestructive testing with broad usefulness in many applications, for instance, metal detection, cracked detection and thickness measurement. Some researchers [1-4] use a detector coil to induce an eddy current over the metal product. As a result, the impedance of the detector coil changes when a probe interacts with the test subject. Secondly, one of the theories that can utilize with the eddy current testing is called phase lock loop (PLL). The PLL is based on the concept of comparing the phase of two signals. The different phase between the two signals is used to control the frequency in the loop. The PLL consists of three main parts, the first part is the phase detector which is responsible for detecting the changing of phase and sends out the error voltage from phase detection to the low pass filter. The second part is the low pass filter, which is used to filter the output from the phase comparator in the PLL.

DOI: 10.24507/icicelb.10.03.227

The third part is a voltage controlled oscillator (VCO). This part generates a feedback frequency that can be controlled by the input tuning voltage and also swings over the operating frequency band for the loop. The PLL performance has already been addressed by other authors [5]. [5] utilized the PLL techniques to control a series resonant inverter for induction surface metal hardening.

In recent years, scientists and engineers have been researching various techniques for the weld seam detection. The realization technique utilizes the detector coil in the Wien bridge oscillator circuit and also monitors the change of amplitude of the oscillator [6]. [7] also utilized two inductor coils as the inductive sensors. The primary and secondary coils serve as the transmitter and receiver coil respectively. In this case [6,7], the weld seam was detected by monitoring the amplitude of the voltage across the receiver coil. Other researchers [8] apply the Lorentz force eddy current testing to detecting the defect in the conductor material. The conductive material moves with the constant velocity relative to a permanent magnet. The interaction between the magnetic field and the induced eddy current can be used to detect the defect in the conductive material.

The advantage of this article is that the oscillating frequency for the detector coil has been adjusted and controlled by the PLL circuit, which can monitor the changing phase and frequency in real time. Unlike the other technique [6,7], which had been mentioned in the literature, those papers only monitor the changing output amplitude when finding the defect in the test subject. Therefore, the purpose of this article is to provide the improvement of convenience and efficiency as an eddy current testing solution. The next section will describe the proposed system analysis and the experimental result.

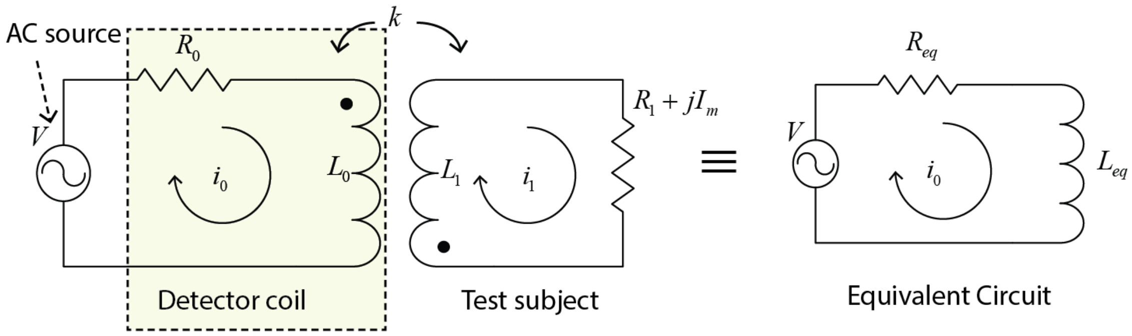

Figure 1. Eddy current transformer model

2. **Eddy Current Transformer Model.** [9] proposed the eddy current transformer model to consider the equivalent circuit between the detector coil and the test subject. This model modifies an impedance of the detector coil and the test subject to be a primary coil and the secondary coil of the transformer as shown in Figure 1. The resistor (R_0) and the inductor (L_0) at primary coil represent the resistance and inductance of the detector coil. The test subject resistor (R_1), the test subject inductor (L_1) and the imaginary of the test subject (jI_m) represent the resistance, the inductance and the leakage inductance of the test subject respectively shown in the left-hand side of Figure 1. The equivalent circuits for both detector coil and test subject are shown on the right-hand side of Figure 1. k is coupling coefficient between L_0 and L_1 which depend on the displacement between the detector coil and the test subject. The complex impedance of the equivalent circuit (Z_{eq}) has been representing in Equation (1a). The equivalent resistor (R_{eq}) represents the resistance in the real part of Equation (1a) and the equivalent inductor (L_{eq}) represents the inductance in the imaginary part of Equation (1a). Finally, R_{eq} and L_{eq} can be identified from Figure 1 as demonstrated in Equations (1b) and (1c).

$$Z_{eq} = R_{eq} + j\omega L_{eq} = R_0 + jL_0\omega + \frac{k^2 L_0 L_1 \omega^2}{R_1 + jL_1\omega + jI_m} \tag{1a}$$

$$L_{eq} = L_0 - \frac{(\omega k)^2 L_0 L_1 (L_1 + I_m/\omega)}{R_1^2 + (I_m + \omega L_1)^2} \tag{1b}$$

$$R_{eq} = R_0 + \frac{(\omega k)^2 L_0 L_1 R_1}{R_1^2 + (I_m + \omega L_1)^2} \tag{1c}$$

where the pulsation ω is related to frequency as $\omega = 2\pi f$. From Equation (1b), the equivalent inductor (L_{eq}) decreases due to the induced eddy current increased, whereas, the equivalent resistor (R_{eq}) in Equation (1c) increases [1] due to the induced eddy current increased.

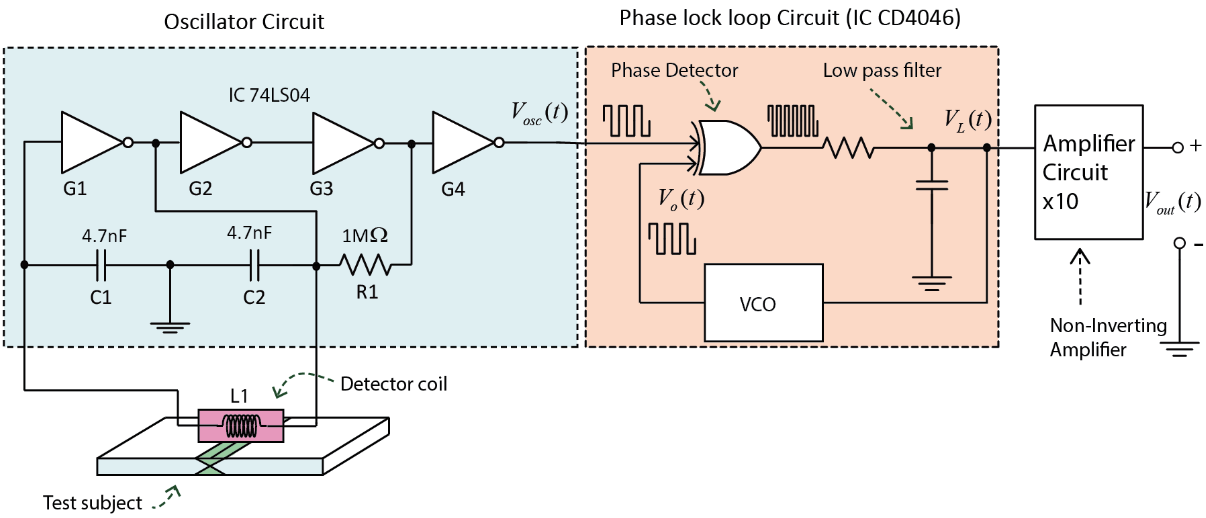

FIGURE 2. Proposed system overview

3. **The Proposed System and Phase Lock Loop Analysis.** The three main circuits as shown in Figure 2 were selected to design the weld seam detector. The first circuit is the oscillator circuit, which is responsible for generating the square wave signal that will change the frequency when the inductance of the detector coil has changed. The second circuit is a phase lock loop circuit, which functions to maintain the frequency and output the voltage from the phase detector where $V_{osc}(t)$ and $V_L(t)$ are the oscillation voltage and the output voltage respectively. The third circuit is the amplifier circuit that was constructed by using the non-inverting amplifier circuit.

The low-pass filter is connected to the output of phase comparator which supplies the average voltage to VCO input and causes the VCO to oscillate at the central frequency. The proposed system was constructed by commercially available. IC CD4046 is used as a phase lock loop and IC 74LS04 is used as the not gate. The single inductor is about 50 mH. It was utilized to be the detector coil. Moreover, the Colpitts oscillator was utilized to be the detector coil for this article. It is one of oscillators which are configured by using the Inductor-Capacitor (LC type). The key feature of the Colpitts oscillator [10] needs only a single inductor. The frequency of the oscillator depends on the detector coil and two capacitors C_1 and C_2. The LC components limit the frequency to the oscillating frequency that can be approximated by using the following equation.

$$f_{osc} = \frac{1}{2\pi\sqrt{L_{eq}\frac{C_1 C_2}{C_1 + C_2}}} \tag{2}$$

From Equation (2), the frequency domain of oscillation frequency is inversely proportional to the inductance of detector coil. In the case of the proposed system, the output frequency is 48 kHz when the detector coil is very close to the test subject. This frequency is the input for the PLL circuit. This proposed system focuses on the changing frequency that can detect the defect or weld seam line in the test subject. Unlike the previous technic [6], it monitors only the changing amplitude which is more unstable than the proposed system. Also, the block diagram of PLL for Laplace transforms in the phase domain is illustrated in Figure 3, where $\phi_{osc}(s)$ is a phase of oscillation frequency functions from the oscillator circuit. $\phi_o(s)$ is a phase output functions from the VCO. $\phi_d(s)$ is a different phase function. $V_L(s)$ is a loop filter output. $V_d(s)$ is a different voltage output. k_d is a gain of the phase detector. k_v is a gain of the VCO. A is an amplifier. ω_o is a frequency output of the VCO. $F(s)$ is the transfer functions of the low pass filter. $V_{out}(s)$ is an output voltage function of the proposed system.

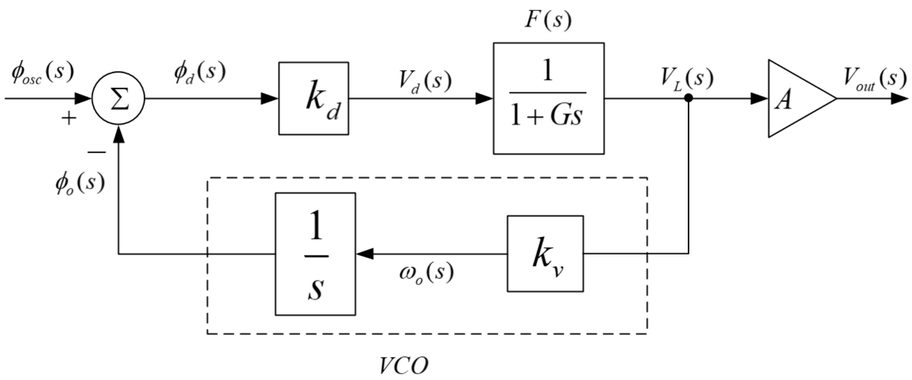

Figure 3. The structure of an eddy current testing based on PLL for weld seam detector

From Figure 3, the relation of the system can be written as Equations (3) and (4)

$$V_L(s) = F(s)k_d[\phi_{osc}(s) - \phi_o(s)] \tag{3}$$

$$\phi_o(s) = \frac{1}{s}k_v V_L(s) + \frac{1}{s}\omega_r(s) \tag{4}$$

where ω_r is a running frequency of the VCO. From Equations (3) and (4), the phase output function of the VCO ($\phi_o(s)$) is presented in Equation (5)

$$\phi_o(s) = \frac{1}{s}k_v(F(s)k_d[\phi_{osc}(s) - \phi_o(s)]) + \frac{1}{s}\omega_r(s) \tag{5}$$

Then, Equation (5) is rewritten as the following equation by representing $F(s) = \frac{1}{1+Gs}$

$$Gs^2\phi_o(s) + s\phi_o(s) + k_v k_d \phi_o(s) = k_v k_d \phi_{osc}(s) + \omega_r(s) + Gs\omega_r(s) \tag{6}$$

Take inverse Laplace transform of both sides of Equation (6) and also assume $k_v k_d = K$.

$$G\frac{d^2}{dt}\phi_o(t) + \frac{d}{dt}\phi_o(t) + K\phi_o(t) = K\phi_{osc}(t) + G\frac{d}{dt}\omega_r(t) + \omega_r(t) \tag{7}$$

From Equation (7), the derivative of running frequency ω_r equal to zero due to the fixed frequency is generated by the VCO at the initial time. Also, the solution for $\phi_o(t)$ can be rewritten by solving the differential equation that the natural and force response is mainly considered. Moreover, the right-hand side of Equation (7) can be identified to be zero to determine the force response solution. $\phi_{osc}(t)$ is assumed as $\phi_{osc}(t) = \omega_k t + \theta_k$, where ω_k is the oscillation angular frequency. Furthermore, $\phi_o(t) = at + b$ is assumed where a and b are constants. Finally, Equation (7) can be identified by replacing $\phi_{osc}(t)$ and $\phi_o(t)$. The following equation is the solution after finish the second order solving.

$$\phi_o(t) = \omega_k t + \theta_k + \frac{1}{K}(\omega_r - \omega_k) \tag{8}$$

$$f_k = nf_{osc} = \frac{n}{2\pi\sqrt{L_{eq}\frac{C_1C_2}{C_1+C_2}}} \tag{9}$$

$$\phi_d = \phi_{osc}(t) - \phi_o(t) = \frac{\omega_k - \omega_r}{K} = \frac{2\pi f_k - 2\pi f_r}{K} = \frac{\frac{n}{\sqrt{L_{eq}\frac{C_1C_2}{C_1+C_2}}} - 2\pi f_r}{K} \tag{10}$$

From Equation (10), it implies that the phase difference is directly proportional to the phase of oscillation frequency that is the output of the oscillator circuit. Also, to determine the voltage output of the proposed techniques, the differential equation solving needs to be recalculated again with a transfer function as Equation (11)

$$V_{out}(s)Gs + V_{out}(s) = Ak_d\phi_d(s) \tag{11}$$

Take the inverse Laplace transform of both sides of Equation (11). The solution is shown as follows.

$$G\frac{dV_{out}(t)}{dt} + V_{out}(t) = Ak_d\phi_d(t) = \frac{Ak_d}{K}(\omega_k - \omega_r) \tag{12}$$

From Equation (12), it can be solved by utilizing the differential equation solving as same as the previous method. Finally, the voltage output of the proposed technique can be expressed as the following equation.

$$V_{out}(t) = \frac{Ak_d n(2\pi f_{osc})}{K} - \frac{Ak_d n(2\pi f_r)}{K} = \frac{Ak_d n\left(\frac{1}{\sqrt{L_{eq}\frac{C_1C_2}{C_1+C_2}}}\right)}{K} - \frac{Ak_d n(2\pi f_r)}{K} \tag{13}$$

Finally, the oscillation frequency depends on the equivalent inductor in Equation (13) that is the inductance of the detector coil. When the detector coil finds the defect in the test subject, the equivalent inductor increases because the defect obstructs and reduces the eddy current as Equation (1b) [1]. Consequently, the output voltage depends on the oscillation frequency and inversely proportional to the equivalent inductor.

4. **Experiment Setup and Test Result.** To verify the proposed technique, Figure 4 demonstrates the diagram of the experiment setup for verifying the proposed system. ANET A8 3D printer is used to be the test station for this article. It can be manually controlled and communicated to the PC via USB 2.0. The detector coil is installed to ANET A8 at nozzle position, and the velocity was set to the minimum about 3.57 mm/s. The test subject was formed by using two metal sheets with a thickness of 6.2 mm; both metal sheets were welded by a double-v joint technique which is the technique for auto theft used to replace the register number of the stolen car with the new legitimate number. The test area has a length of 100 mm and width of 40 mm. The start point is the left-hand side of the test area as shown in Figure 4. The eddy current and PLL circuit were constructed using the component in Figure 2. The supply voltage usage is $\pm 5V$, and the voltage gain of amplifier circuit was set to 10. Also, the test subject was sprayed by the black color to hide the weld seam.

When starting to test, the test subject is moved through the detector coil in the Y-axis 100 mm. After completing the Y-axis, the test subject returned to start point again and shift to the X-axis 2 mm and forward in Y-axis again. Finally, the test result can be plotted in the 2-D and the 3-D result after finishing this test about 20 rounds and all test result was plotted by MATLAB 2018 student version. Figure 5 shows the voltage drop when the detector coil finds the weld seam joint and detects the negative peak amplitude

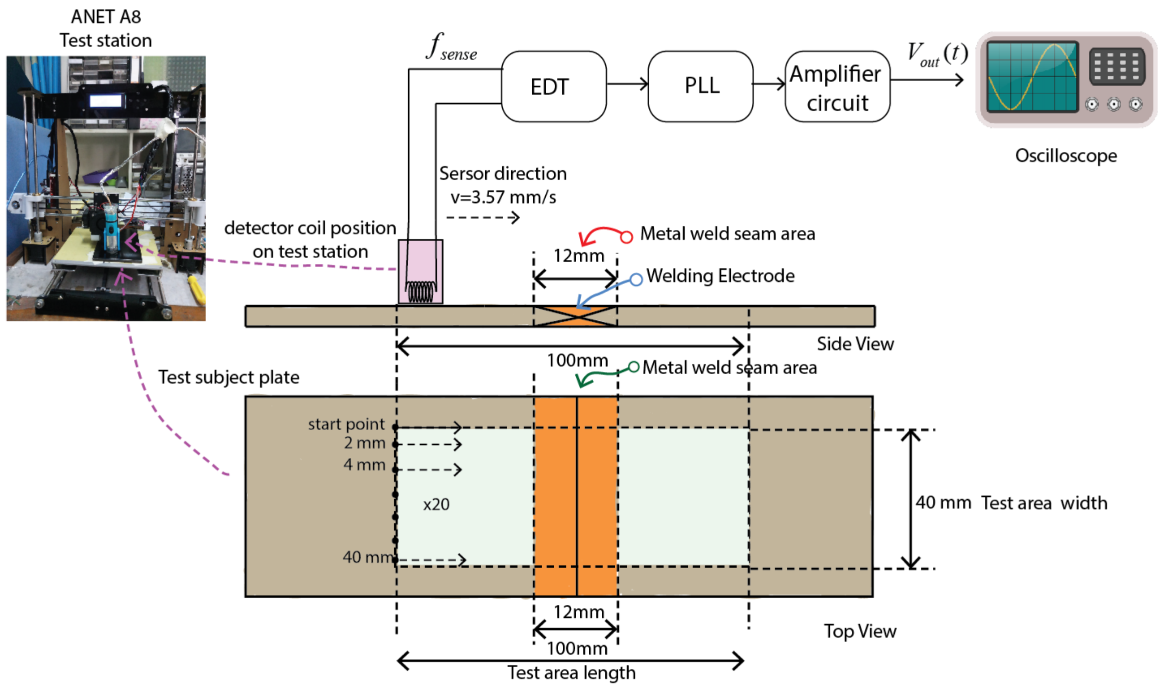

FIGURE 4. Diagram of the experiment setup

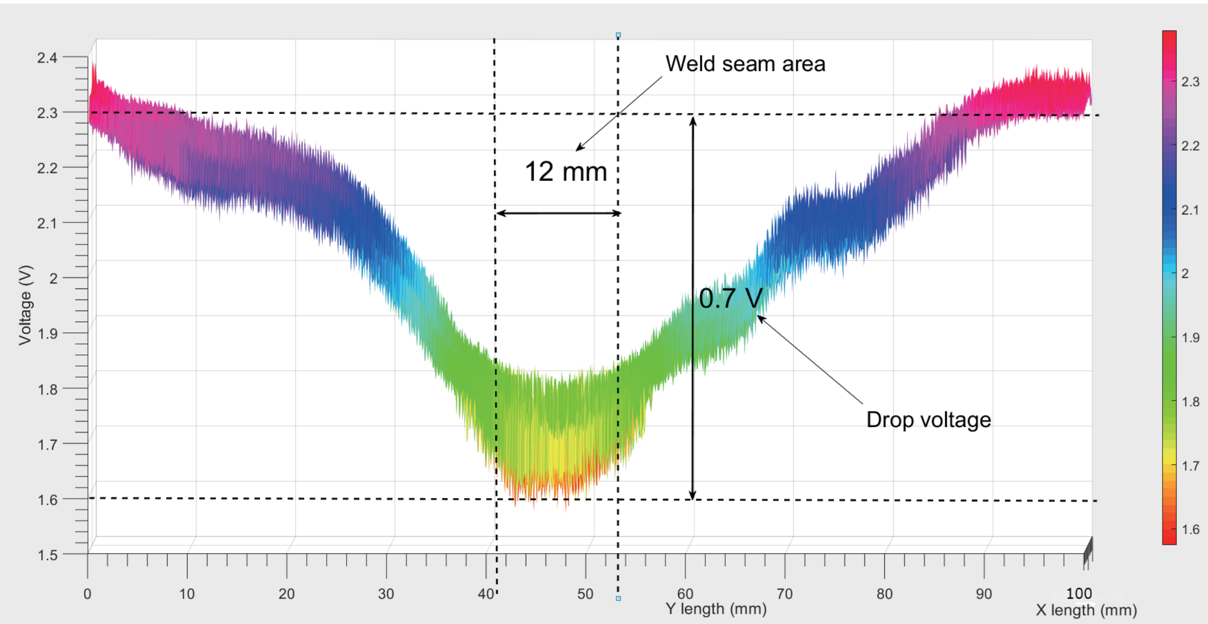

FIGURE 5. The voltage drop when the detector coil finds the weld seam joint

is about 0.7 V at the weld seam line position. Figure 6 shows the voltage drop in the 3-D overview. It is evident that in the weld seam line and V-joint range about 12 mm can be detected by the proposed system in the form of 2-D and 3-D result. As a result, the main advantage of the proposed system is the weld seam area which can be detected by using the frequency domain that is more stable than the amplitude domain and the 3-D result can be used to show the weld seam area that is more comfortable than the 2-D result shown in the oscilloscope.

5. **Conclusions.** The weld seam detector of satisfactory performance designed based on eddy current testing and PLL techniques has been described in this article. The main

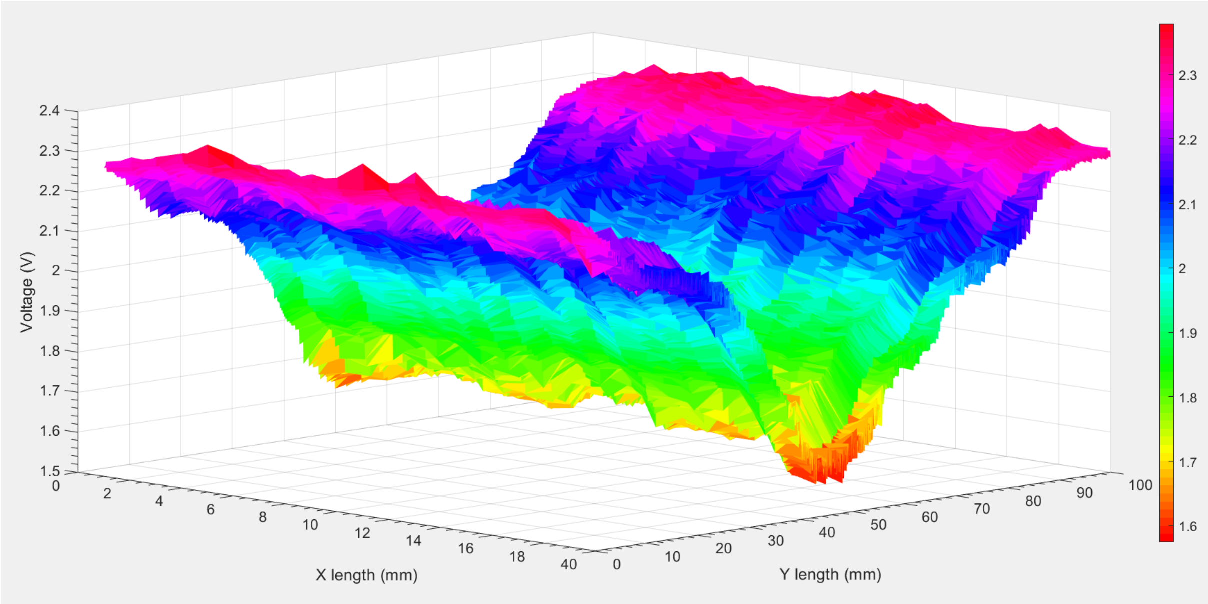

Figure 6. The test results in 3-D surface view

objective of this study focuses on how to apply the eddy current and phase lock loop theory to designing the weld seam detector circuit. Furthermore, the experimentcal results in 2-D and 3-D result can show the weld seam range about 12 mm that is the real defect of test subject under color coating. This paper can create system compatibility with eddy current testing. Future work should include the real stolen car chassis to verify the proposed system and continue this research to the new application.

REFERENCES

[1] G.-M. Javier, G.-G. Jaime and V.-S. Ernesto, Non-destructive techniques based on eddy current testing, *Sensor*, vol.11, pp.2525-2565, 2011.

[2] K. B. Ali, A. N. Abdalla, D. Rifai and M. A. Faraj, Review on system development in eddy current testing and technique for defect classification, *IET Circuit Device & System*, vol.11, pp.303-343, 2017.

[3] H. A. Sidano, Non-contact eddy current excitation method for vibration testing, *Experiment Mechanics*, vol.46, pp.627-635, 2006.

[4] W. Cheng, Thickness measurement of metal plates using swept-frequency eddy current testing and impedance normalization, *IEEE Sensor Journal*, vol.17, no.4, 2017.

[5] B. Meziane and H. Zerong, Improved efficiency determination for a PLL-controlled series resonant invertor for induction metal surface hardening, *IEEE Industry Applications Society Annual Meeting*, United States, 2015.

[6] T. Gasosoth, A. Kaewpoonsuk and K. Prompak, Single search coil weld seam detector based on eddy current technique, *ICIC Express Letters*, vol.8, no.4, pp.1199-1203, 2014.

[7] K. Anucha, G. Thitinun and R. Apinai, A simple weld seam detector based on eddy current testing, *SICE Annual Conference*, Sapporo, Japan, 2014.

[8] B. Hartmut, Z. Marek and T. Hannes, Defect detection in conduction material using eddy current testing techniques, *Serbian Journal of Electrical Engineering*, vol.11, no.4, pp.535-549, 2014.

[9] D. Placko and I. Dufour, Eddy current sensors for nondestructive inspection of graphite composite material, *Industry Application Society Annual Meeting*, vol.2, pp.1679-1682, 1992.

[10] A. M. O. Obiazi and F. I. Anyasi, Metal detector utilizing the colpitts oscillator with toroidal coil, *Journal of Engineering and Applied Science*, vol.5, pp.56-63, 2010.