# Design and Optimisation of Mutual Inductance based Pulsed Eddy Current Probe

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## Abstract

High lift-off inspection arising from thick insulation and requirement to protect probe from weld zones are challenges to pulsed eddy current (PEC) testing. In traditional PEC probe with fixed coil gap, weakening interaction between probe and test sample as lift-off increases reduces sensitivity. To analyse this influence, numerical simulation and experiments on design and optimisation of driver-pickup PEC probes are carried out. Results validate that both coil gap and lift-off have significant effects on resultant mutual inductance of driver-pickup PEC probes above test samples. In addition, the probe sensitivity is enhanced at a higher lift-off when coil gap exceeds a certain value. The increase in detection lift-off with coil gap could be optimised.

Keywords: lift-off, mutual inductance, coil gap, sensitivity.

## 1. Introduction

Different types of PEC probe arrangements exist in literature and selection depends on applications such as inspection of complex geometric surfaces, buried objects, thick insulated structures and weld areas [1]. PEC Probe configurations include excitation coil and magnetic sensor probe which uses one coil for excitation and magnetic sensor to pick-up the response signal. Although this type of probe has high sensitivity, only the excitation coil could be optimised [2]. Another type is absolute probe [3] where one coil is used for both excitation and detection of impedance variation. The absolute impedance variation measured by this type of PEC probe configuration reveals much information about the tested sample, but the resistor-inductor (RL) circuit used to measure the response signal is too sensitive to temperature variations [4]. Differential-Mode probe consists of two connected coils that are placed on adjacent parts of test sample. One of the sensing coils is wound to oppose the magnetic field of other coil to reduce the offset voltage caused by the primary magnetic field. The output of the probe is zero when there is no defect on the sample. The non-zero output results when defect alters the voltage offset of the pickup coil [5]. The driver coil of this type of probe is commonly connected to a RL circuit while the pickup coil output signal may be applied directly to the input of differential amplifier. The major strength of this probe is sensitivity with high spatial resolution. However, because the coils are too close to each other, gradually propagating defects are very difficult to detect. Another type of PEC probe is driver-pickup probe, which uses two unconnected coils one for excitation and the other for sensing the response signal. It is the induced voltage from the pickup coil that is used for defect detection. Major limitation of this type of probe is low defect detection especially at low frequency[6]. Although magnetic field sensors [7, 8] are currently used in place of the pickup coils to mitigate this weakness, some strength of driver-pickup coils probe makes it outstanding for PEC applications. Enhanced capabilities for driver-pickup PEC probe, including improved signal-to-noise ratio in the presence of changing lift-off, directional properties, capability of optimisation of individual coils of the probe made it a good choice for PEC probe [9].

Sensitivity of driver-pick-up eddy current probe significantly depends on mutual inductance (magnetic couplings) among driver coil, pick-up coil and test sample [10]. Therefore, investigating the influence of these mutual inductances on sensitivity of PEC probe will give insight for its sensitivity improvement. Research on improving sensitivity of driver-pick-up probes has been reported in [11] where offset signal generated by the excitation signal was compensated by differential coil configuration. Although this approach improved sensitivity , another coil was added to compensate the offset signal increasing space and cost .Research to improve sensitivity based on lift-off is also reported in [12, 13]. However, normalisation technique as used in the report definitely degrades sensitivity. The approach in [14] used the peak value of the difference signal to reduce lift-off but with a complicated measurement. A transformer approach was used through electrical equivalent circuit analysis in [15] to mitigate the effect of lift-off in thickness measurement. However, only one coil probe is considered but exploiting the potentials of driver pick-up coil will better enhance sensitivity. Although much research to mitigate lift-off effect has been done, there is still a challenge to inspect at high lift-off. In this work we consider rectangular coils because of its characteristic potentials when compared to other coil shapes. The features of rectangular coils considered include its high sensitivity to surface scratches and subsurface defects, directional property, capability of creating uniform eddy current flow and can be configured to operate in differential and driver-pick-up mode [16-18].

The mutual inductance of a driver-pick-up PEC probe above a conductor is a superposition of mutual inductances emanating from magnetic couplings among coils and test sample. One between them in free space and another is due to the coupling with the conductor. One contributed by the conductor gives the information about defect in the test specimen not the one between coils in space. In fact, the mutual inductance between coils in free space causes excitation signal to induce an intrinsic offset voltage in the pick-up coil. Because analysis and quantification of defects mainly depend on eddy current signal, the induced intrinsic offset voltage in the pick-up coil is equivalent to noise .Different techniques have be used to reduce the direct coupling between coils in order to improve SNR [11]. Coil winding is used to induce phase shift between two excitation coils to cancel out the offsets in the pick-up coil in [11]. However this technique is limited by nonlinearity errors and sensor drift emanating from magnetic hysteresis. And also more space is required by using more excitation coils thereby limiting its implementation in printed circuit board. In [19], ferrite sheet was used to reduce the direct coupling between driver and pick-up coils with improved sensitivity. The limitation of this technique lies in the fact that some part of eddy current generated field would also be diverted by the ferrite thereby reducing the information signal strength [20].

The proposed solution is to use driver-pick-up probe configuration to improve detection sensitivity at a given lift-off. We study the influence of coil gap and lift-off on mutual inductance of PEC probe above a test sample with a view to obtain maximum output voltage with lift-off and coil gap variations. The rest of the paper is organised as follows. In Section 2, mutual inductance based PEC method and its application in PEC non-destructive testing are discussed. We also explain the analytical model of mutual inductance between coils above conductor in PEC testing. Section 3 is on simulation of the parameters influence on mutual inductance in conjunction with analytical model and optimization design technique. While Section 4 is on experimental validation of the simulation results. Finally, Section 5 derives the conclusion and highlights future work.

# 2. Mutual Inductance Based Pulsed Eddy Current Testing Method

A driver-pick-up type of PEC probe basically consists of a coplanar driver and pick-up coil pair (Figure 1a). The driver coil is excited with a time-changing current which develops a changing magnetic field. This field induces eddy current in nearby electrical conductor. According to Faraday's law, an electromotive force (emf) is developed both in the drive and pick-up coils due to the changing magnetic flux emanating from the driver coil current [10, 21]. The ratio of the induced emf to the rate of change of current producing it on the driver coil itself and on the pick-up coil are known as self-inductance and mutual inductance of the PEC probe, respectively. The coil geometries and their relative positions determine these self and mutual inductances. Also, the magnetic field developed by the probe induces eddy currents (EC) in the nearby conducting material. The ECs in the conductor develop an opposing magnetic field that generates an additional (emf) in both coils according to Lenz's law. This opposing magnetic field changes the resultant mutual inductance of the probe as shown in Figure1b. Because EC develops magnetic flux that is not in phase with the exciting current, a lossy Self-inductance is generated by the coil coupling to the ECs it generates. Also, a lossy-mutual inductance is generated when a coil couples to the ECs generated by a nearby coil. These lossy inductances are complex-valued and frequency-dependent [10, 21, 22] . To derive the relationship between mutual inductance among coils and test sample as a function of coil gap and lift-off, we start from the voltage developed in the pick-up coil in absence of test sample. And then modify the parameters caused by eddy current flow in the conductor when the probe is above a conductor.

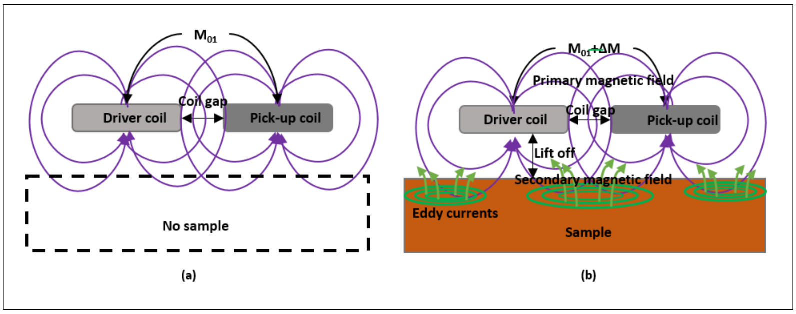


Figure 1. Driver-Pickup PEC probes (a) without sample and (b) with sample

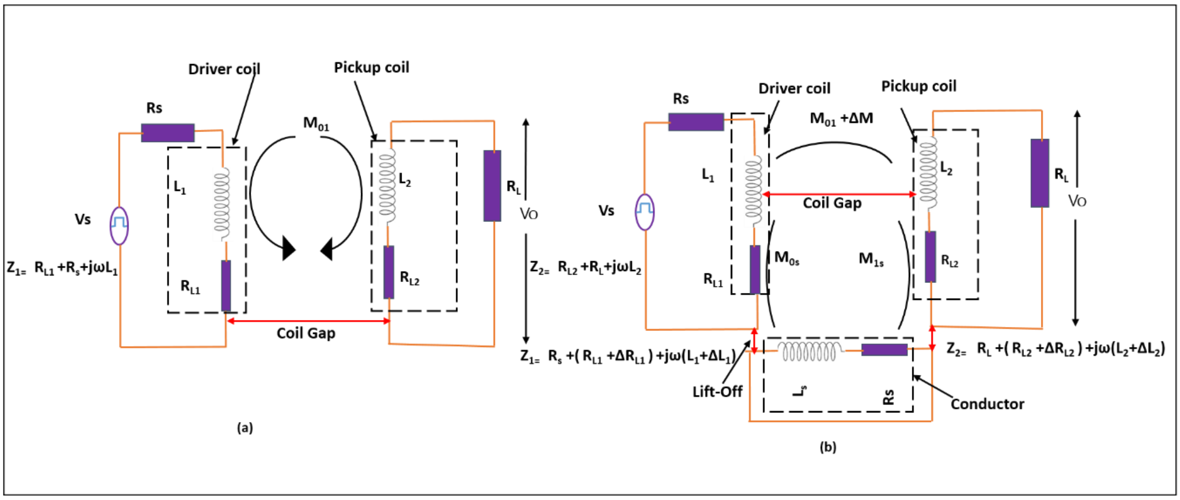


Figure 2 Equivalent circuits of PEC probes (a) without sample and (b) with sample

The output voltage of the pickup coil in absence of a conductor, as illustrated in Figure2a, is derived in [23, 24] as

$$V_0 = \frac{-J\omega M_{01} V_s R_L}{Z_1 Z_2 + (\omega M_{01})^2} \text{.......................................} (1)$$

Where $V_0$ = pick-up Voltage, $M_{01}$= mutual inductance between driver and pick-up coil in absence of conductor, $V_s$ = excitation voltage, $R_L$ = load resistance, $Z_1$ = driver coil impedance, $Z_2$ = pick-up coil impedance, $R_{L1}$= resistance of driver coil, $R_{L2}$= resistance of pick-up coil, $R_s$ = signal source resistance, $L_1$ = driver coil inductance, $L_2$ = pick-up coil inductance. When the probe is above a conductor, parameters are modified by the eddy current flow in the conductor as follows: RL1= $R_{L1}$+ $\Delta R_{L1}$, $L_1$= $L_1$+ $\Delta L_1$, $R_{L2}$= $R_{L2}$+ $\Delta R_{L2}$ , $L_2$= $L_2$+ $\Delta L_2$ , $M_{01}$= $M_{01}$+ ΔM. where $\Delta R_{L1}$, $\Delta R_{L2}$, $\Delta L_1$, $\Delta L_2$, ΔM are variations of the parameters and other mutual inductances $M_{0s}$ = mutual inductance between driver coil and conductor, $M_{1s}$ = mutual inductance between pick-up coil and conductor are introduced [10].Pick-up voltage $V_0$ significantly depends on mutual inductance between driver and pick-up coil in absence of conductor as shown in equation (1). However, in presence of conductor (Figure 2b) induced eddy current in the conductor disturbs the electromagnetic field, hence the pick-up voltage cannot be predicted based on mutual inductance of the driver and pick-up coils only. Therefore the modified relationship becomes

$$V_0 = \frac{-J\omega(M_{01}+\Delta M)V_s R_L}{(Z_1+\Delta Z_1)\,(Z_2+\Delta Z_2)+(\omega(M_{01}+\Delta M))^2} \text{.........} (2)$$

Change in mutual inductance ΔM as functions of Coil gap and lift-off has been reported in [25]. Also the transfer impedance from eddy current to driver coil $\Delta Z_1 = \Delta R_{L1} + J\omega\Delta L_1$ and to pick-up coil $\Delta Z_2 = \Delta R_{L2} + J\omega\Delta L_2$ defined as change in mutual impedance (transfer impedance) when the probe is above test sample and in the absence of the sample significantly depend on lift-off as shown in equation (3) [26].

$$\Delta Z(L) = r(L)\frac{\omega^2 M^2\,(L)}{r^2\,(L)+\omega^2 l^2(L)} - l(L)\frac{\omega^2 M^2\,(L)}{r^2\,(L)+\omega^2 l^2(L)} \ldots\ldots (3)$$

Where $L$= lift-off, r = resistance of eddy current circulation path, $l$ = inductance of eddy current circulation path, M = mutual inductance between coil and eddy current circulation path. Putting equation (3) in (2) and M as $M_{0s}$, $M_{1s}$ for driver and pickup coils.

$$V_0 = \frac{-J\omega(M_{01}+\Delta M)V_s R_L}{\left(Z_1 + r_1\frac{\omega^2 M_{0s}^2}{r_1^2+\omega^2 {l_1}^2} - j\omega l_1\frac{\omega^2 M_{0s}^2}{r_1^2+\omega^2 {l_1}^2}\right)\left(Z_2 + r_2\frac{\omega^2 M_{1s}^2}{r_2^2+\omega^2 {l_2}^2} - j\omega l_2\frac{\omega^2 M_{1s}^2}{r_2^2+\omega^2 {l_2}^2}\right) + \omega^2(M_{01}+\Delta M)^2} \ldots\ldots (4)$$

From Equations (2) and (4), it can be seen that the pick-up voltage $V_0$ largely depends on mutual couplings among coils and test sample. Variations of mutual inductances as a result of coil gap and lift-off invariably influences the value of pick-up voltage. Mutual inductance of the coils above a conductor is a superposition of one between coils in the air and that from the conductor given by ($M_{01}$ + ΔM). It is the change in mutual inductance due to the conductor ΔM that bears the information signal about the conductor [25] .Therefore, the mutual inductance ΔM largely affects the sensitivity of the PEC probe which is defined as change in amplitude of the response signal due to presence of metal conductor. The analytical derivation of the mutual inductances among coils and sample as a function of coil gaps (d) and lift-off (L) is very complex and sometimes impossible depending on coil geometry, hence we choose numerical simulation approach. Numerical simulations [27, 28]are carried out as explained in the next Section to understand the influence of lift-off and coil gap on the pick-up coil voltage.

# 3. Numerical Simulation Study

Figure 3 is the geometry and PEC probe configuration for the simulation study. To simulate the operation of the probe above a conductive sample, a 3D model was built in COMSOL Multiphysiscs software. The model is made up of rectangular block (400x300x50 mm) and two rectangular coils of 36 x25 mm each for both driver and pickup coil of the probe. The model is placed in a volume with electromagnetic properties of air to truncate the simulation volume. The material of coil is setup as copper with electrical conductivity $5.8\times10^7$ S/m and relative permeability 1. The sample is setup as aluminium material with relative permeability 1 and electrical conductivity $4.0\times10^7$ S/m [29] . A pulse signal at 1 kHz frequency is used for excitation of the driver coil. To reduce computation time and resources the model is simplified using 2D models [30]from the cross sections of the 3D geometry. This simplifies the geometry without reducing the integrity of the model. Numerical model used is free tetrahedral finite element with about 183000 mesh elements and 33000 boundary elements .The simulation procedure is as follows: excitation was applied on driver coils and pick-up coil voltage is measured and recorded. Through changing of the lift-off ranging from 1to 37 mm with a step of 4 mm and coil gaps (centre to centre) ranging from 25 mm to 70 mm with a step of 5mm, we analyse their influence on the output voltage of the pick-up coil. The voltage $V_0$ is as a result of the equations (2), (3) and (4) which show that pick-up voltage $V_0$ depends on mutual inductance which invariably is a function of coil gap and lift-off. Hence variation of $V_0$ with coil gap and lift-off is obtained from the simulation. Reference-subtracted, of peak amplitudes of pick-up coil voltage, the reference being the probe in air, without the effect of the conductor [31]are used in the study and discussed in section 3.1.

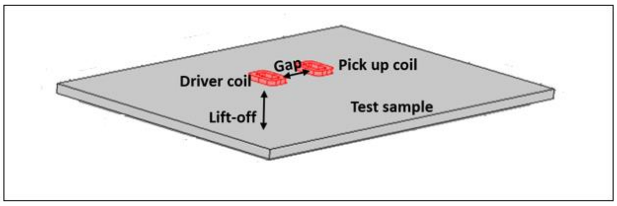


Figure 3. Simulation model showing driver, pick-up coils and test sample

## 3.1 Lift-Off Influence

As mentioned in Section 2, the change in mutual inductance due to eddy current in test sample carries the information about the condition of the sample. Hence the reference-subtracted signal used in this analysis is the voltage induced in the pick-up coil by eddy current in the sample which is obtained by subtracting pick-up coil voltage in presence and in absence of test sample. In order to analyse the influence of lift-off on the reference-subtracted signal, a plot of reference-subtracted voltage against lift-off is shown in Figure 4.

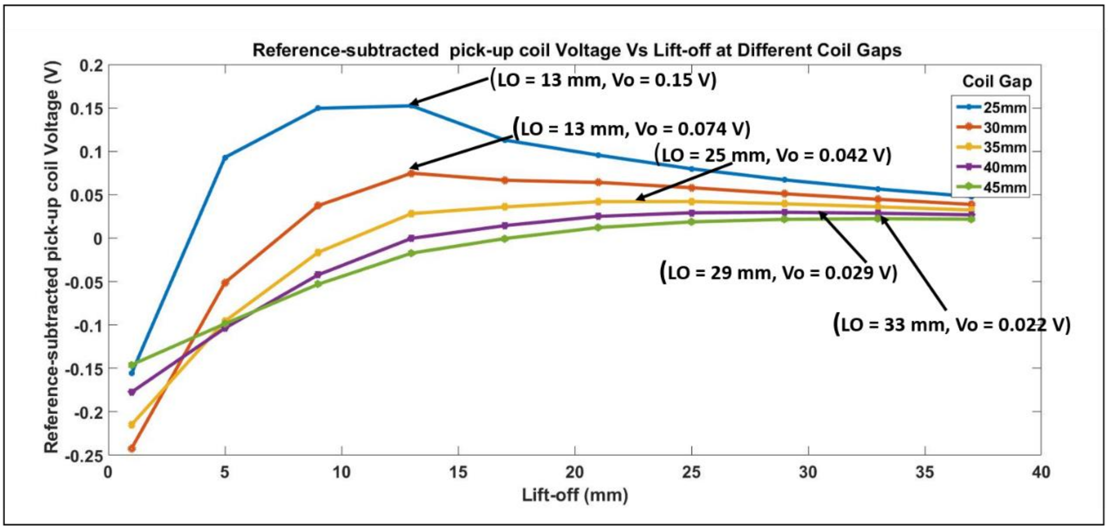


Figure 4 Lift-off influence on reference-subtracted signal from simulation

From Figure 4, we can see points where maximum values of reference-subtracted signal are located as indicated with arrows. The lift-off (LO) and pick-up voltage (Vo) values are also indicated. Generally, sensitivity grows and decays exponential before and after maximum value respectively .The maximum point at coil gap of 25 mm occurred at L0 =13 mm, Vo = 0.15 V. Also at coil gap 30 mm, maximum point occurred at the same Lo = 13 while with lower Vo (0.074 V). As the coil gap increased to 35 mm and above, maximum point occurred at higher L0 but with reduced Vo including coil gap 35 mm (Lo =25 mm,V0 = 0.042 V),40 mm (L0 = 29 mm,V0 = 0.029 V) and 45 mm (L0 = 33 mm,V0 = 0.022 V). This shows that although the sensitivity decreases with increase in coil gap, as coil gap increases beyond certain value, the probe sensitivity is maximum at a higher lift-off. The reason is that at maximum lift-off, the opposing eddy current signal equals the offset signal generated by the excitation field in the pick-up coil. This almost eliminates the offset signal in the pick-up coil. At null offset any change in eddy current caused by defect or any other factor in the test sample shows a maximum change of the response signal. This implies improved sensitivity at that coil gap/lift-off. In section 4.3 experiments, we validate this with surface crack detection of aluminium sample and compared sensitivity at various lift-off. And results show that highest sensitivity is achieved at the lift-off where reference-subtracted is maximum.

## 3.2 Coil Gap Influence

The relationship between coil gap and reference-subtracted of pick-up coil voltage is obtained as shown in Figure 5. There is a general exponential behaviour of the signal as coil gap increases. It can be observed that at lower lift-off, as coil gap increases the reference-subtracted signal first decreases before increasing exponentially. However, as lift-off increases eddy current influence is reduced and the signal only decays exponentially but with increase in signal amplitude. The reference-subtracted signal behaviour is hence a function of both coil gap and lift-off. Then sensitivity at high lift-off can be achieved by optimal combination of coil gap and lift-off especially where spatial constraints is required in printed circuit board based PEC probes.

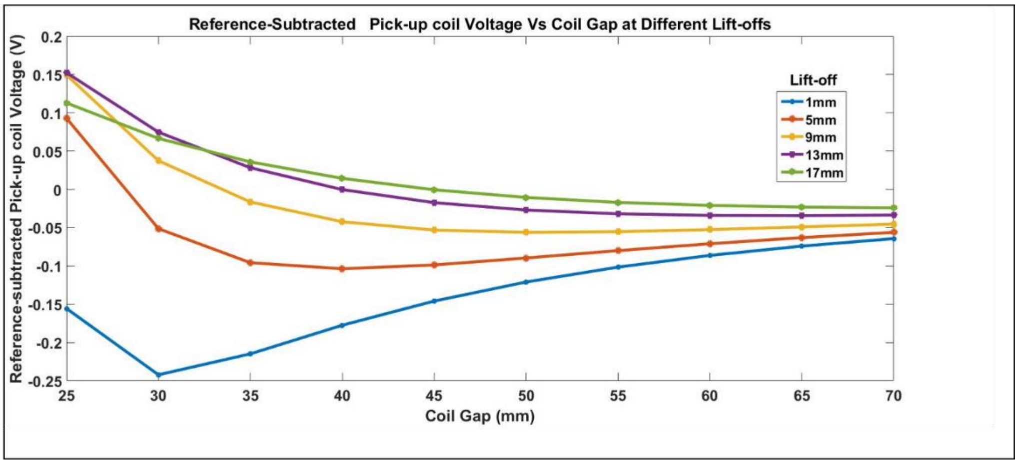


Figure 5. Coil gap influence on reference-subtracted signal from simulation.

# 4. Experimental Study and Validation

Experimental validation of the numerical simulation is performed with two rectangular planar coil of equal size as driver and pick-up coils and dimensions as described in section 3.

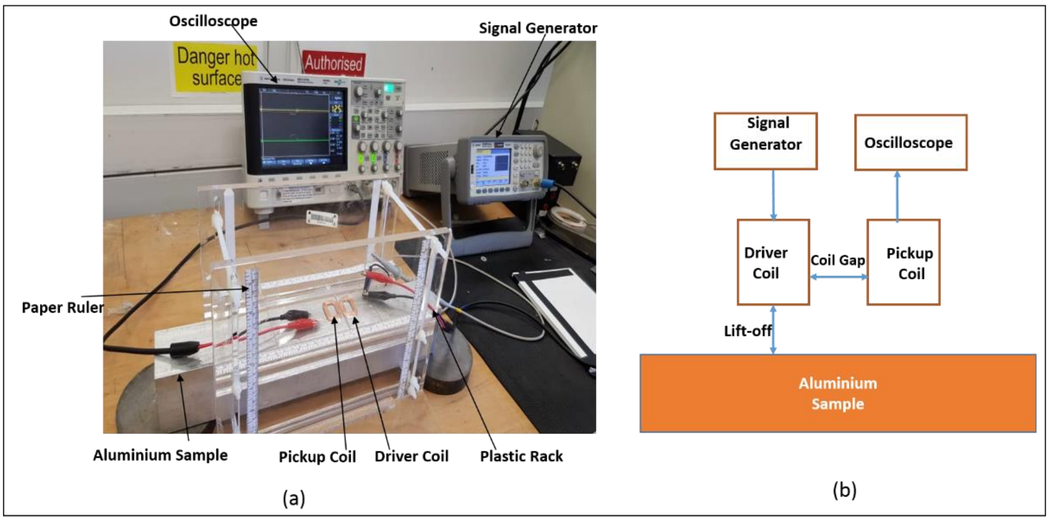


Figure 6. Experimental setup for PEC probe (a) Instruments and sample setup (b) block diagram

The Experimental setup and the block diagram of materials used in this paper is shown in Figures 6a and 6b respectively. The PEC probe as described in simulation including signal generator, oscilloscope, driver and pick-up coils are connected as shown in Figure 6a above. Pulse signal of amplitude 5 V at frequency of 1 kHz was supplied to the driver coil and amplitude of output of the pick-up coil is read and recorded from the oscilloscope. For every measurement the voltage drop in the driver is kept constant at 460 mV by varying the amplitude of the pulse signal from the signal generator. Aluminium Sample measuring 400x65x50 mm is used. Lift-off is varied from 1 mm to 37 mm at a step of 4 mm. For every lift-off, coil gap is varied from 25 mm to 70 mm at a step of 5 mm and output voltage of the pick-up coil is read and recorded. Reference-subtracted signal is obtained by subtracting output voltage of pick-up coil in absence of sample and in presence of sample. The influence of lift-off and coil gap on the reference-subtracted signal is discussed below.

## 4.1 Lift-off Influence Analysis

The experimental results for lift-off influence on reference-subtracted of pick-up coil voltage are shown in Figure 7. The pick-up signal shows the same trend as in simulation result of Figure 4. As can be seen there is also maximum values at Lo = 13 for both coil gaps 25 mm and 30 mm as in the simulation result. Again sensitivity grows and decays exponential before and after maximum value respectively. Also as the coil gap increased to 35 mm and above, maximum point occurred at higher L0 but with reduced Vo. The difference in the simulation and experimental results is that the enhanced sensitivity at higher lift-off seems to occur at the same value of lift-off for different coil gaps once the coil increases to 35 mm and above. This difference can be attributed to little variation in driver coil voltage little variation as lift–off changes which is not kept constant in simulation study.

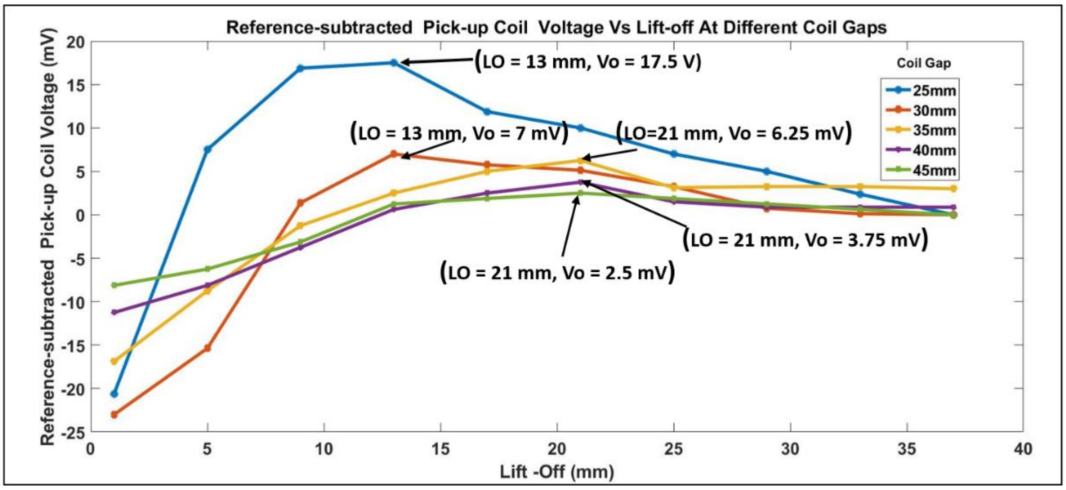


Figure 7. Reference-subtracted pick-up voltage vs lift-off at different coil gaps

## 4.2 Coil Gap Influence Analysis

The coil gap influence also agrees with the simulation results show in Figure 7. As coil gap increases, the signal amplitude decreases .It can be seen that at lower lift-off as the coil gap increases, reference-subtracted voltage decreases to a minimum value and then increases exponentially. Specifically the signal decreases to a minimum at 30 mm coil gap and then grows exponentially. However as lift-off increases the influence of test sample reduces and gradient of the signal decreases. So experiment validates that pick-up voltage due to eddy current is influenced by coil gap and lift-off and there is a certain coil gap that is exceeded for maximum high lift-off sensitivity to be achieved.

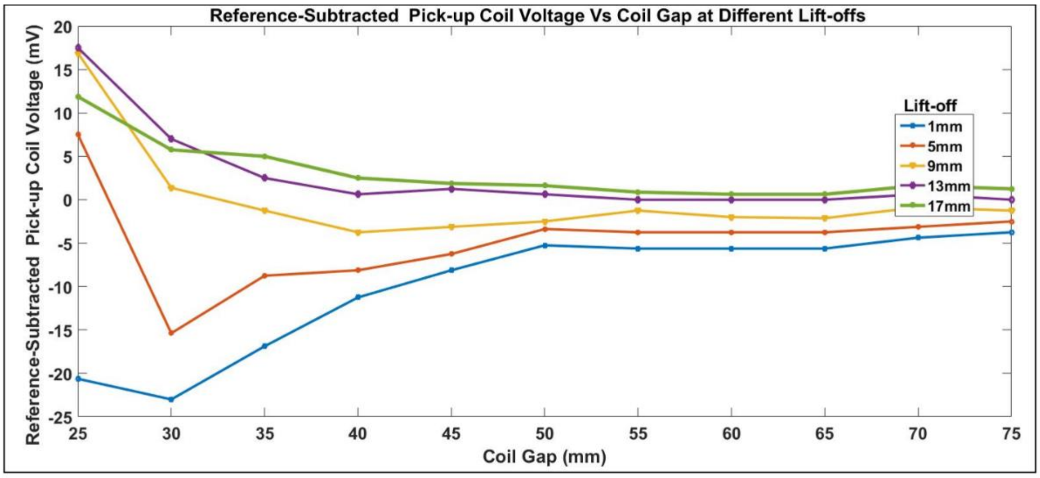


Figure 8. Reference-subtracted signal pick-up voltage vs coil gap at different lift-offs

The major source of noise apart from minor lift-off variations and hence signal-to-noise ratio (SNR) can be explained from the pick-up signal which consists of two parts: the offset signal generated by the excitation signal due to $M_{01}$ and the signal induced by the eddy current in the sample due to ΔM. Hence, on the surface of a sample, the pick-up signal is the offset signal superimposed on the eddy current signal. Because analysis and quantification of defects mainly depend on eddy current signal, the offset signal is equivalent to noise. Hence signal-to-noise ratio (SNR) is defined as

$$\mathrm{SNR} = \frac{\mathrm{Max(PA)+Max(PE)}}{\mathrm{Max(PA)}} \quad \ldots \ (3)$$

where Max (PA) and Max (PE) are maximum of pick-up signal in air and eddy current signal respectively. Increase in lift-off reduces eddy current signal while increase in coil gap reduces offset signal. Therefore signal-to-noise ratio (SNR) decreases with increase in lift-off but increases with increase in coil gap. In addition, weak eddy current signal at high lift-off will be difficult to identify, hence the sensitivity of the probe to defects is significantly decreased. Increasing the coil gap will be helpful to reduce the offset signal but at the same time, the magnetic field strength in the sample will be reduced. However, there is coil gap/lift-off, the opposing eddy current signal cancels the offset signal generated by the excitation field in the pick-up coil. This almost eliminates the offset signal in the pick-up coil. At this null offset coil gap/lift-off, any change in eddy current caused by defect or any other factor in the test sample shows a maximum change of the response signal. Therefore, for every coil gap, there is a lift-off in which eddy current signal nulls the offset signal thereby improving SNR.

## 4.3 Comparison of Simulations and Experimental Results

Table 1: Experimental and simulations results at selected lift-off and coil gaps.

| Experiment | | | | | Simulation | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Coil Gap (mm) | Lift-off (mm) | Max (PA) (mV) | Max (PE) (mV) | SNR | Coil Gap (mm) | Lift-off (mm) | Max (PA) (mV) | Max (PE) (mV) | SNR |
| 25 | 9 | 93.13 | 17.50 | 1.18 | 25 | 9 | 92.06 | 14.94 | 1.16 |
| | 13 | 93.13 | 16.88 | <u>1.20</u> | | 13 | 92.06 | 15.00 | <u>1.19</u> |
| | 17 | 93.13 | 11.88 | 1.13 | | 17 | 92.06 | 11.29 | 1.12 |
| 30 | 9 | 41.75 | 7.00 | 1.03 | 30 | 9 | 45.5 | 3.74 | 1.10 |
| | 13 | 41.75 | 1.38 | <u>1.17</u> | | 13 | 45.5 | 7.48 | <u>1.16</u> |
| | 17 | 41.75 | 5.75 | 1.14 | | 17 | 45.5 | 6.66 | 1.15 |
| 35 | 17 | 26.25 | 6.25 | 1.19 | 35 | 17 | 30.9 | 3.58 | 1.12 |
| | 21 | 26.25 | 5.00 | <u>1.24</u> | | 21 | 30.9 | 4.19 | <u>1.14</u> |
| | 25 | 26.25 | 3.13 | 1.12 | | 25 | 30.9 | 4.21 | 1.13 |
| 40 | 17 | 18.75 | 3.75 | 1.13 | 40 | 17 | 22.7 | 1.44 | 1.06 |
| | 21 | 18.75 | 2.50 | <u>1.20</u> | | 21 | 22.7 | 2.50 | <u>1.13</u> |
| | 25 | 18.75 | 1.88 | 1.10 | | 25 | 22.7 | 2.90 | 1.13 |
| 45 | 17 | 13.75 | 2.50 | 1.14 | 45 | 17 | 17.44 | 1.13 | 1.06 |
| | 21 | 13.75 | 1.88 | <u>1.18</u> | | 21 | 17.44 | 1.87 | <u>1.10</u> |
| | 25 | 13.75 | 1.88 | 1.14 | | 25 | 17.44 | 1.78 | 1.10 |

To compare simulations and experimental results, we employ SNR explained in Section 4.2. The SNR shown in table 1 is used to compare experimental and simulation results of the proposed approach. For a given coil gap, three lift-off values are selected: lift-off before the maximum SNR, at maximum SNR and after the maximum SNR. The maximum values of SNR are underlined in the table. It can be seen that for every coil gap there is a lift-off where maximum SNR is achieved for both experimental and simulation results. For instance for coil gap 25 mm, three lift-off values of 9 mm, 13 mm and 17 mm are shown and the maximum SNR of 1.20 occurred at 13 mm lift-off while both lift-off values of 9 mm and 17 mm had lower values of 1.18 and 1.13 respectively for experimental result. Simulation results have the same trend of SNR but with different maximum values of 1.19 and lower values of 1.16 and 1.12. The same trend can be observed from other coil gap and lift-off values. The difference in values can be attributed to little variation in driver coil voltage as lift-off changes which is kept constant only in experiment but was varying in simulation study. Hence there is a good agreement between simulation and experiment results that pick-up voltage due to eddy current is influenced by coil gap and lift-off and there is a certain coil gap that is required for maximum lift-off sensitivity (SNR) to be achieved.

## 4.4 Performance Evaluation of the Proposed Technique for Crack Detection

To evaluate an improved sensitivity at optimal lift-off for a given coil gap, aluminium sample with artificial crack Figure 9e is scanned at three selected lift-offs. First, at the optimal lift-off, second above optimal lift-off and third below the optimal lift-off respectively. Figure 9a shows variation of pick-up signal with lift-off without crack and it is observed that the optimal lift-off for coil gap 20 mm is established at 20 mm with a maximum pick-up signal amplitude of 0.0114 V. Two other lift-offs selected for scan are 4mm with pick-up signal amplitude of 0.0069 V and 40 mm with signal amplitude of 0.0106 V. This is followed by scanning the aluminium sample with crack at lift-offs of 4 mm, 20 mm and 40 mm respectively so as to compare their amplitude change due to crack. AS amplitude change feature is used for the crack detection, it is shown in Figures 9b to 9c that lift-off 20mm (optimal) scan has the highest amplitude change of 0.0117 V Figure 9c, while Lift-off 40 mm Figure 9d and 4 mm Figure 9b has 0.0109 V and 0.0062 V respectively. Therefore scanning at optimal lift-off of 20mm has stronger response than responses from other lift-offs with enhanced crack detection sensitivity. The experimental study has evaluated that optimal sensitivity can be achieved with optimised coils gap and lift-off. This is important in design and development of a new driver-pick-up pulsed eddy current probe for a specific lift-off requirement.

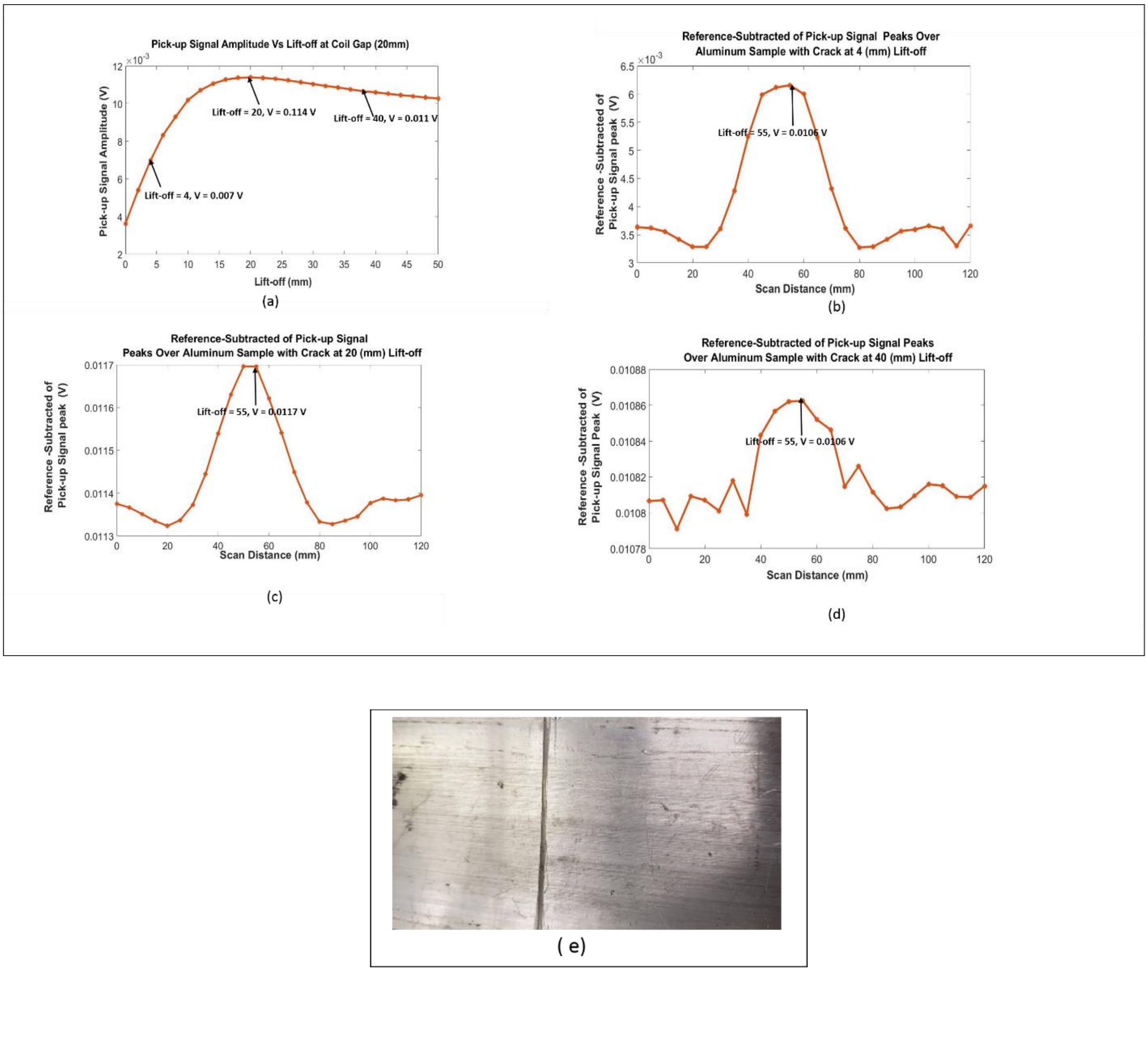


Figure 9 .Comparison of crack detection at different lift-offs with fixed coil gap

## 5. Conclusion and future work

This paper applies numerical simulation and experimental studies of design and optimisation of driver-pick-up PEC probes for high lift-off NDT&E applications. Simulations and experimental studies of coil gap and lift-off influence on mutual inductance based PEC probe have been performed. It is found that both coil gap and lift-off influence probe sensitivity and their sensitivity can be optimised through selection of driver-pick-up coil gap and lift-off. Also, the probe sensitivity is enhanced at a higher lift-off at a certain value of coil gap. The enhancement of sensitivity at a higher lift-off at a certain value of coil gap could be used in inspection of buried objects and structures with thick insulation where high lift-off is unavoidable requirement. The design can also be applied for inspection of pipeline with welds. More field studies, and different coil sizes and configurations with appropriate signal condition will be investigated in future work.

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