Characterization of Defect for Magnetic Flux Leakage in Non-Destructive Test using I-Kaz^{tm}

Nor Afandi Sharif, Rizauddin Ramli, Mohd Zaki Nuawi, Khairulbadri Ahmad

Abstract: The application of hall sensors in Magnetitic Flux Leakage (MFL) has played an important role in Above Storage Tank (AST) on detection of defect caused by corrosion to improve productivity and to avoid catastrophe. The MFL sensor measured magnetic flux distribution in three axes B_x, B_y and B_z. Currently, there are several signal monitoring methods constructed by analysing MFL signal distribution upon defect detection. This paper presents the methodology of optimized Integrated Kurtosis-based Algorithm for Z-filter (I-Kaz^{TM}) Coefficient using multilevel signal decomposition technique to analyse the MFL signal distribution on the defect in the correlation of MFL scanning device speed and position. The MFL scanning device comprises 11 hall effect sensors position in array coupled with a linear guide to ensuring a constant velocity of scanning. In order to obtain an optimum signal distribution, I-Kaz^{TM} 3D is proposed as one of the derivatives of I-Kaz^{TM} to analyse multiple velocities of scanning. The characterization of the defect can be estimated by analysing the deflection of magnetic flux leakage in the y-axis, B_y as the scanner approach the defect region before being analysed by I-Kaz^{TM} from the beginning until the end of the workpiece.

Keywords* : *Magnetic Flux Leakage, Kurtosis-based alghorith, I-KAZ^{TM} , Hall effect sensors

I. INTRODUCTION

The Magnetic Flux leakage (MFL) is one of the reliable Non-Destructive (NDT) testing applied widely in flaw detection of plate and pipelines [1] resulted from long-term wear out and surrounding conditions. The deformed pipe and plate bring difficulty in safe operation due to corrode, cracked and deformed and it will bring a severe situation if it caused an oil-gas leakage [2]. MFL technique detects the defect volume of metal loss is frequently used in above storage tank (AST) by analyzing the shape of detected flaws before it can be classified to identify the severity of the damage [3]. The MFL detection system comprises two basic elements which are the method of detecting a leakage field and a method for magnetization. The presence of anomaly captures by the sensor in the magnetic property of the material if any defect presence.

A statistical model often has been used by the researcher to evaluate and translate the signal into approximate data of depth, with and length due to indirect measurement of MFL type of evaluation[4]. In 2008, Sophian et al. [5] used Principle Component Analysis (PCA) as one of a statistical technique for extraction and classification of Pulsed Eddy Current (PEC) data. Within this technique, frequency analysis and peak point can be examined to identify defect characterization. More recent, Ding et al. (2016) [6] applied a Response Surface Methodology (RSM) to optimized input parameter values and validate the relationship between variable and response by using statistical fitting method before using Finite Element Analysis (FEA) to validate the optimized parameter.

Furthermore, approximate linearity between the relation of defect length and distribution of the leakage field has also been studied by other researchers. The length and depth of the defect is interrelated because both of the components contributes to the magnitude of flux leakage [7]. In this paper, we propose a methodology for characterizing the defect of length and depth in the metal plate with various thick and designated defects using a novel statistical approach by implementing optimized Integrated Kurtosis-based Algorithm for Z-filter (I-Kaz^{TM}) [8]. The acquired signal in the review criteria experiment will be decomposed into three frequency ranges comprises low-frequency (LF) range of 0 – 0.25fmax, a high-frequency (HF) range of 0.25fmax – 0.5fmax and a very high- frequency (VF) range of 0.5fmax.

On the other hand, Neural network (NN) signal analysis technique as one of artificial intelligent (AI) tools also been used widely in the MFL inspection due to its ability to provide solution in complex data analysis [9]. The defect characterization has been improved by implementing NN type analysis in a previous study [10][11]. Joshi (2008) [12] and Ramuhalli (2002) [13] studied the estimation of a 3D geometry defect in predicting maximum allowable operating pressure (MAOP) in a pipe due to inaccurate signal interpolation by applying wavelet neural network to identify the correlation between defect MFL signal and geometric parameters [14]. It shows that NN has faster convergence rate and fit better for the approximation of the multivariable function as long as the defect area is properly targeted [15].

The application of Finite Element Method (FEM) based simulation is another technique for investigate the behavior of MFL signal on the defect region in

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microscopic level and defined as a forward problem. [16]. The parameter of the material e.g.: length and depth can be evaluated based on the filed distribution on the reconstructed defect region and defined as an inverse problem [17]. FEM is the common computer numerical simulation due to its ability to accommodate circular geometric problem, non-linear and time dependent [18]. Ji et. al. (2003)[19] studied the application of FEM under various type of material, defect sizing and magnetization. The study applies 3-D FEM to generalized the potential formulation on the magnetic field intensity and modelled detail comparison on part with defect and without defect. The issues magnetic field around the transmission also can be solved caused by voltage conductor, circular and others.

II. INSPECTION SYSTEM

The system design comprised of 11 hall effect sensors position in array placed between two strong Neodymium magnets as shown in figure 1. The MFL component is placed on the ballsrew type linear guide couple with the stepper motor to help maintain the desired speed. The permanent magnet will magnetize the test piece with from north to south. Figure 1 shows the position of the MFL detection system (scanner) used in the research.

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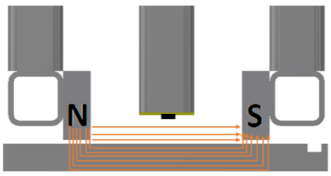
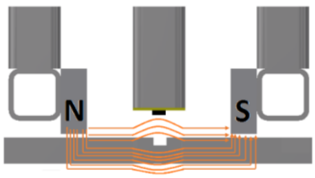


(i)



(ii)

Figure 1 Principle on the MFL signal detection

Figure 1 (i) shows the scanner under a normal condition without any flaws detected. As the scanner move along x-axis, the developed magnetic flux will eventually have induced through the fabricated flaws and effect the magnetic flux distribution on the particular area as shown in Figure 1 (ii).

Figure 2 shows that the MFL system incorporated with the following components; a power source, processing unit, and personal computer. The flux density, β is a unit derived from the metal loss area is then converted into a serial number (0-1023) in the signal processing unit (Arduino MEGA) before it being converted to Voltage, V in the personal computer using MATLAB Simulink software. The usage of the stepper motor is to ensure the consistency in scanner velocity along the x-axis which can be controlled using the potential meter by modulating its analogue input to the stepper motor controller.

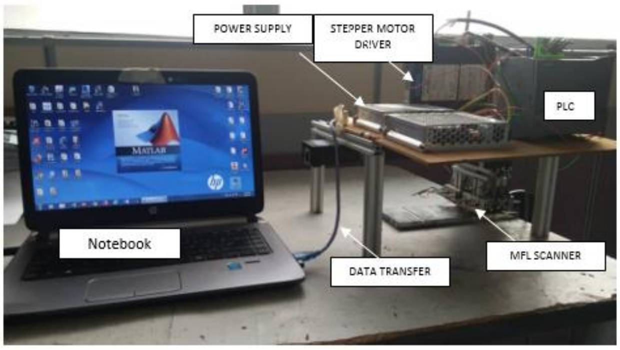


Figure 2 MFL inspection system

III. SYSTEM OPERATION

The MFL scanning system is comprising of 11 units of hall sensors array which cover an area of 110 mm width. The voltage signal, V from H1 to H12 is sent to the signal processing before it is converted to a serial number as a digitized value before it's transferred into the software. Hall sensor reading is then collected individually and amplified to achieve its voltage value. The arrangement of the operational block in MATLAB SIMULINK is shown in figure 3 illustrated the input of each hall effect sensor coupled with the gain value before being translated to the voltage, V. All the inputs then combined together in the multiplexer block before it's been plotted in real time.

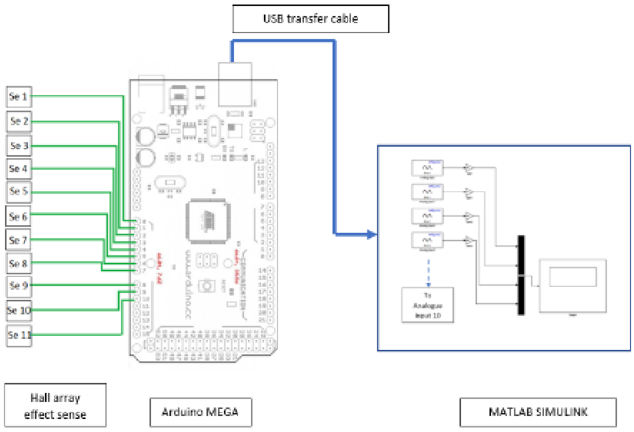


Figure 3 Connection of Hall array effect sensor to Arduino and MATLAB SIMULINK

Table 1 show items and specification of the MFL inspection system. Arduino MEGA is used as the processing unit in the system due to the dynamic and high speed in data transfer using Integrated

Development Environment (IDE) as a software developer[20][21] . In order to have a reliable signal processing and recording, a Dell Desktop is used in processing the serial signal from Arduino MEGA into meaningful data through USB cable.

Table 1 Items and specification of the MFL inspection system.

No.	Item	Specification
1	Hall sensor	Manufacture: Honeywell SS496A Solid State Hall Effect Sensor Dimension: 4 mm (w) × 3 mm (h) Supply Voltage: regulated 5 V Output Operating Range: 0.5–4.5V
2	Processing Unit	Arduino Mega 2560 Microcontroller: ATmega2560 Operating Voltage: 5V Input Voltage (recommended): 7 ~ 12V Digital I/O Pins: 54 (of which 14 provide PWM output) Analog Input Pins: 16
3	Signal Processing and date recording	Dell Desktop Processor: Intel(R) Core™ i3 CPU 3.3 GHz Memory (RAM): 4.00 GB System type: 64-bit Operating System System operated: Windows 7 Ultimate

V. SIGNAL PROCESSING AND STATISTICAL ANALYSIS

The hall sensor used in the experiment is from Honeywell (SS496A) with a typical current 3.5 mA with a voltage supply of 5 V. The ratio between V_{out} over B be to determine the sensitivity of the Hall effect as shown in Figure 4.0 with ±840 Gauss magnetic range sensitivity.

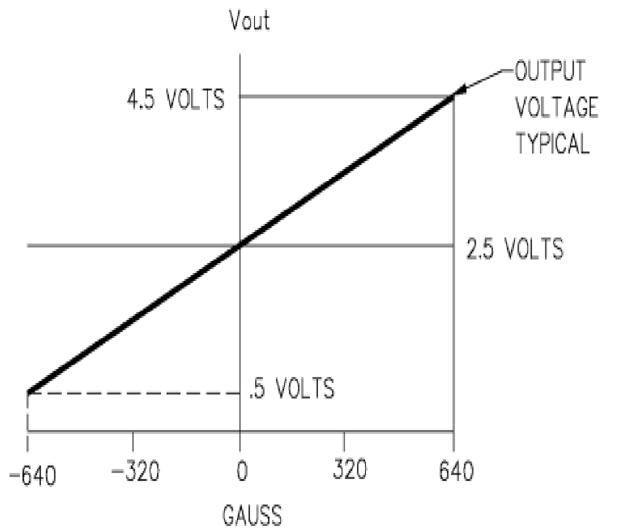


Figure 4 Characteristic of Hall effect sensor.

Figure 4 shows the flow chart of the signal processing throughout the MFL scanning device. The flow is then detailed in figure 5 showing the 11-array hall effect sensor Se00 to Se10 channelled from Arduino MEGA to MATLAB SIMULINK. The data is then SIMULINK is coupled together with the position displacement, x (mm) to render a 2-D array matrix composition data.

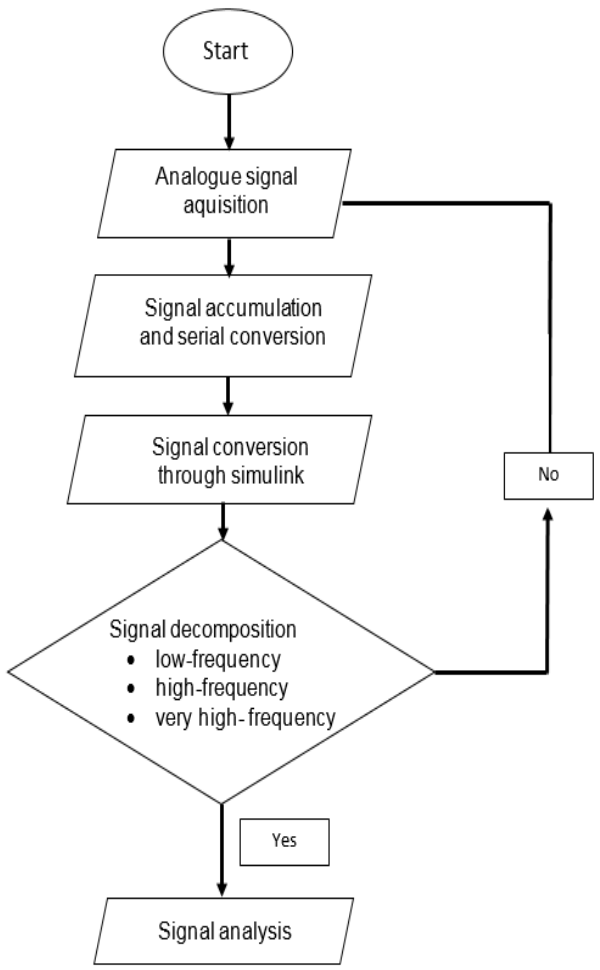


Figure 5 Flow chart of the signal processing in MFL scanning system

When the scanning is completed, all data will be recorded into specific files before it can analyse further. The data is then analysed using I-Kaz™ statistical process to decompose the frequency into three frequency range. The variance σ^2, measure the scattering of data distribution for each frequency group (time depending) in order to determine the average magnitude deviation in a single point as shown in equation (1) [22].

$$\sigma_L^2 = \frac{\sum_{i=1}^{N}\left(x_i^L - \mu_L\right)^2}{N};\ \sigma_H^2 = \frac{\sum_{i=1}^{N}\left(x_i^H - \mu_H\right)^2}{N};\ \sigma_V^2 = \frac{\sum_{i=1}^{N}\left(x_i^V - \mu_V\right)^2}{N}; \qquad (1)$$

The data variances for *i*-sample data σ_L^2, σ_H^2 and σ_V^2 show the ranges of low frequency (LF), high frequency (HF) and very high frequency (VF) in time respectively. The I-Kaz™ coefficient Z^∞ can be written in term of variance since it is developed by the concept of data scattering in equation 2 and 3.

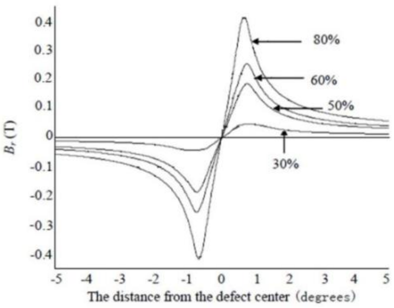
……..(2)

$$Z^{\infty} = \sqrt{\left(\sigma_L^2\right)^2 + \left(\sigma_H^2\right)^2 + \left(\sigma_V^2\right)^2} \quad ..(3)$$

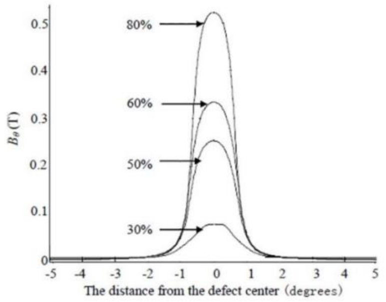
$$Z^{\infty} = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i^L - \mu_L\right)^2}{N^2} + \frac{\sum_{i=1}^{N}\left(x_i^H - \mu_H\right)^2}{N^2} + \frac{\sum_{i=1}^{N}\left(x_i^V - \mu_V\right)^2}{N^2}}$$

Kurtosis (K) is a 4th statistical moment that is very sensitive to spikiness of the data used to identify a defect occur in high amplitude [23]. It also is best used in signal observation in evaluating the shape of the data distribution and the mean deviation to the waveform peak [24].

The signal relationship between MFL signal and defect geometries also analyses in this research focusing on the depth of defect on y-axis. More complete picture can be analyzed as the defect shape is varied on the fabricated defect of the workpiece. In this experiment, S45C material with 10 mm and 20 mm thicknesses is used with a fabricated grove to emulate the defect in ASTs. The MFL signal acquisition are collected in y-component B_y of magnetic flux density where, $B = (B_x, B_y, B_z)$. The B_x signal is used for size estimation by detecting the x-component of the defect and useful for defect size estimation [25] but the stray field in the defect region doesn't comprise in a specific region effect the signal distribution and effect the final judgement due to noise. Figure 6 shows the previous experimental result describing two workpieces with a fabricated defect with multiple thicknesses in collecting signal in y-axis and x-axis.



(a)



(b)

Figure 6 (a) Radial component (B_y) of different thickness and (b) axial (B_x) [15]

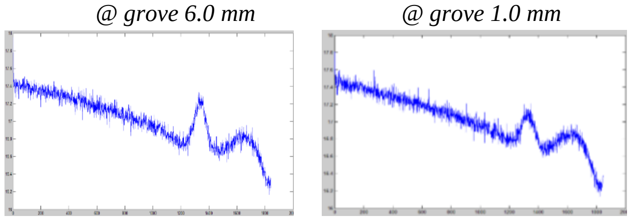
In order to have more reliable data in term of magnetization on the ferromagnetic material, speed of the MFL machine contribute a significant attribute during the analysis [26]. A linear rotary coupled with a stepper motor is used to form a linearly uniform speed with an adjustable motor controller to ensure the minimum effect of velocity on the data distribution [27].

IV. RESULT AND DISSCUSSION

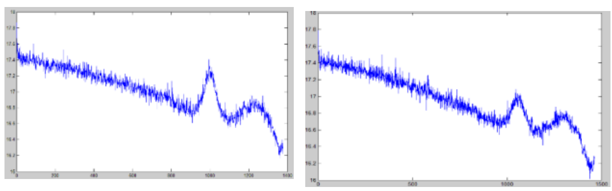
Scanning result is showing the change of signal amplitude (voltage) along the workpiece until it reaches the groove section shown in figure 8.0 by 1000 Hz of sampling time. The density of the signal can be observed significantly by comparing the speed of scanning and the inverse correlation between signal density and acquisition speed in the time domain in both sample 1 and 2 at each run. Each of the speed settings shows different in amplitude for accumulated 12 arrays Hall Effect sensors. The signal values are summed together due to the position of the individual sensor, it is excited differently, for example, those located at the center is more excited from the sensor located at the boundaries of the workpiece due to the position of the array sensors.

The result shows a significant difference in the amplitude peak in figure 8 between sample 1 and sample 2. The amplitude peak in sample 1 (groove thickness 6.0 mm) is slightly higher than sample 2 (groove thickness 6.0 mm) due to the difference of magnitude deflection that correlates of the size of the groves as per shown in the time domain signal spectrum. The speed of acquisition (Runs) also shows a significant signal spectrum density in the groove region (designated defect) by comparing each run of the different sample.

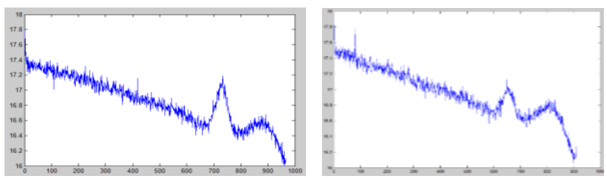
Sample 1: Thickness 10 mm @ grove 6.0 mm | *Sample : Thickness 10 mm @ grove 1.0 mm*



Run 1: Low Speed | **Run 4: Low Speed**



Run 1: Medium Speed | **Run 4: Medium Speed**



Run 1: High Speed | **Run 4: High Speed**

Figure 8 the voltage vs time graph during MFL scanning process on plate with 10.0 mm thickness with 6.0 mm depth of grove (sample 1) and 6.0 mm depth of grove (sample 2) at different speed (runs)

The results of I-Kaz 3D graphical representation of two runs groove 6.0mm thickness and 1.0 mm thickness shows in figure 4.0 is a plot with I-Kaz coefficient Z^{∞} are obtain from I-Kaz statistical process analysis using MATLAB software. The signal data is calculated using equation 2 and 3 and put on each of the runs. The change

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of data scattering in the 3D representation on each of the runs is slightly insignificantly
to one another due to magnetic flux leakage pattern on the groove region compared to I-Kaz coefficient Z^{∞} that showed a significant difference in every run. The I-Kaz coefficient Z^{∞} increasing when the size of the groove becomes deeper on 6.0mm thickness sample. Through the observation, I-Kaz coefficient value is increasing upon speed setting from low to high. The value of Z^{∞} on sample 1 getting larger from 0.1015 at low speed to 0.4635 at a high speed and the same pattern also can be observed in sample 2. The speed of the scanning effect the population of data and result space of scattering and frequency distribution. The result is also aligned with the previous study that

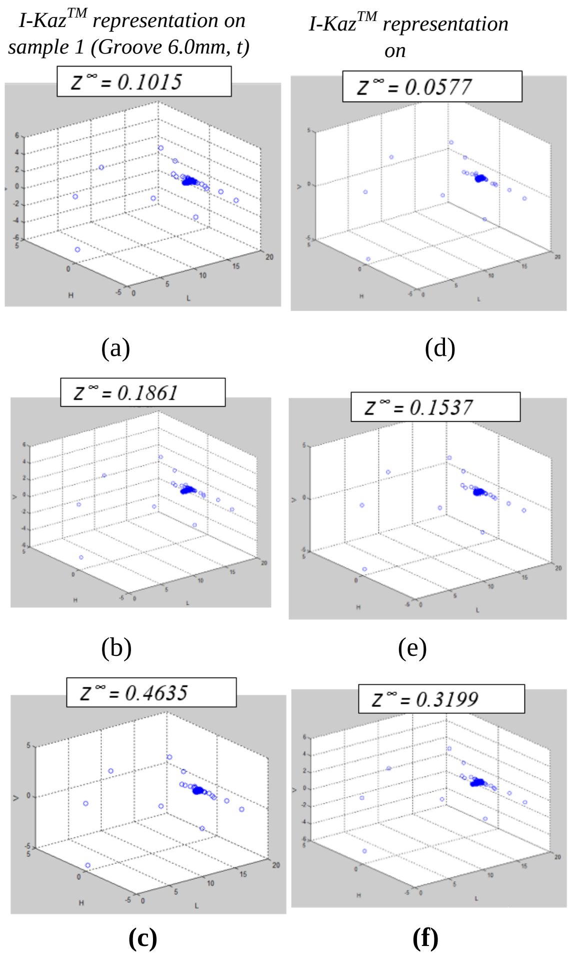

Figure 9.0 I-Kaz 3D representation for Hall effect sensors for sample 1 (6.0 mm groove of depth) and sample 2 (1.0 mm groove of depth) with multiple runs (a) (d) low speed, (b) (e) medium speed and (c) (f) high speed.

V. CONCLUSSION

The development of MFL scanning device comprising 11 hall array effect sensors for defect characterization was presented in this paper. A I-Kaz™ signal monitoring method has been setup and analysed statistically in the context of defect characterization based on two parameters (speed and defect size). The I-Kaz Multi level method is very sensitive to the frequency and amplitude of the signal which suitable to the application of MFL due to its objective in detecting the small change of material lost in NDT. The MFL scanning system consists of 11-array of hall effect sensors providing a good and reliable estimation for the defect profile even the presence of reasonable noise.

The scanning principle of the MFL method is to capture the deflection magnetic flux on the defect in y-direction due to the low tendency of error in the presence of surrounding electromagnetic noise. The data is then captured in MATLAB SIMULINK before I-Kaz™ method as an integrated kurtosis-based algorithm can be applied to detect a small change of the measured signal at the respected position. The signal amplitudes are increased when the size of defect increase and the remain the same in all velocity level in the same sample. The recorded signal is affected by the change of depth in the groove. The signal is increased when the depth of the groves is increased. The relationship with scanning speed and depth of the groves can be visualize using I-Kaz statistical method which is decrease significantly when the depth of the groves decreases. The method is useful in monitoring a slight change in the ferromagnetic material property and helps NDT inspector to locate the affected area before any appropriate action can be done.

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