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FIBER GLASS COMPOSITE LAMINATES (FGCL) MEASUREMENT USING 3 AXIS PULSE ECHO SCANNING UNIT

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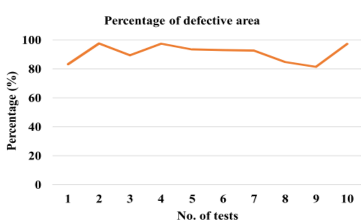
Graphical abstract



Abstract

Ultrasonic is a common non-destructive testing for composite laminates inspection. However, high cost caused limited budget organization to own this equipment for their research activities. Our work seeks to develop an automated and reliable ultrasonic scanning unit with affordable cost. The validation of scanning speed using Arduino UNO Microcontroller has successfully achieved by determined the stepping mode. This prototype is suggested to inspect surface defect on glass fiber composite laminates up to 6 mm in thickness as the probe limitation for optimum scanning performance. The optimum scanning speed for this prototype was 12 mm/sec using micro step setup while the average percentage of different against ten times inspection are as low as five percent.

Keywords: Ultrasonic testing, Fiber Glass Composite Laminates (FGCL), Region of Interest Line (ROIL) materials

Abstrak

Ultrasonik merupakan ujian tanpa musnah yang biasa digunakan untuk pemeriksaan bahan komposit berlapis. Walau bagaimanapun, kos yang tinggi menjadi kekangan utama untuk organisasi kecil tertentu memiliki alat pengujian ini khususnya bagi aktiviti penyelidikan. Kajian kami bertujuan untuk membangunkan unit pengimbas ujian ultrasonic automatik yang boleh dipercayai dengan kos yang berpatutan. Pengesahan kelajuan imbasan menggunakan pengawal mikro Arduino UNO telah berjaya dicapai dengan penentuan jenis mod pelangkah. Prototaip ini dicadangkan untuk pemeriksaan kecacatan pada permukaan gentian kaca komposit berlapis sehingga 6 mm tebal untuk prestasi imbasan yang optimum. Kelajuan imbasan yang optimum untuk prototaip ini adalah 12 mm per saat dengan menggunakan mod pelangkah jenis mikro manakala purata peratus perbezaan bagi sepuluh bacaan pemeriksaan adalah serendah lima peratus.

Kata kunci: Dendritic ujian ultrasonik, gentian kaca komposit berlapis, Kawasan laluan popular

1.0 INTRODUCTION

Over In recent years, there are increasing demand for lightweight and high performance composites laminates especially carbon fiber and fiber glass composite laminates material due to its high performance such as low weight, high strength and stiffness [1]. Nowadays, the composite laminates material demand not only concentrated on giant industry such as aircraft manufacturing, automotive and marine but also varies on other industry such as wind energy and communication. However, Lin Ye *et al.* [2] observed that composite material have been actively improved by major aircraft manufacturer to develop an innovative functionalized materials and structures. Recently, commercial aircraft model Dreamliner B-7E7 manufactured by Boeing and model A380 manufactured by Airbus are the most advanced, economical operation and efficient aircraft. Driven by technological effort made in last few years, application of those composite laminates material expand in recreational market and sport industries. Despite of the growth of composite laminates demanding, the market also struggled with challenging of process control difficulties and insufficient production capacity due to lack of automation. These factor influence the price increase yearly. Since the defect may occur along the production stage and may end up with catastrophic failure during operation, inspection is a vital process to ensure the quality of product. Non-destructive testing which is Ultrasonic testing is the common technique being applied for composite laminates inspection compared to other technique. Moreover, an overview of the advantages and disadvantages of some of the currently available NDT methods are presented by Garnier *et al.* [3]. Hence, insufficient technology and high cost to perform ultrasonic inspection become one of the major reason why small and medium industries with limited budget are not able to take part into this market. Thus, the development of cost effective, portable and reliable is required to identify defect at an early stage of composite laminates structure.

In the past few years, several research on Non-Destructive Testing (NDT) especially ultrasonic testing (UT) has been done especially to improve ultrasonic testing capability in various material using signal and image based from ultrasonic scanning inspection. Several research have been performed using various approach on different material as done by T. Merazi Meksen *et al.* [4] who was developed defect detection system on steel structure using TOFD (Time of Flight Diffraction) technique while J. R. Lee and his research team applied same approach on a pipe [5]. In addition, T. Hasiotis *et al.* [6] used Ultrasonic C-scan approach to determine artificial defect on laminated composite material. On the other hand M. F. Mahmod *et al.* [7] compared an artificial defect of laminated composite material using both signal data acquisition and flatbed scanning result while T. Y. Lim *et al.* [8] use flatbed scanning approach to measure the nose radius of cutting insert. The use of thermography on impacted glass fiber reinforced polymer also being studied by C. Meola *et al.* [9] while some researcher used 3D laser vibrometry to locate delamination on composite plate as performed by W. J. Staszewski *et al.* [10]. Besides, computer tomography which is a part of NDT approach have been studied by C. C. Tsao [11] to evaluate the delamination damage in carbon fiber reinforced composite material caused by drilling operation. Moreover, some researcher tend to study and developed an automated ultrasonic inspection system such as development an automated disbond inspection system using an ultrasonic array for Metal Matrix Composite (MMC) tank track by D. Xiang *et al.* [12], performed an automated buried pipeline condition assessment system in concrete pipes by Shivprakash *et al.* [13], development of portable ultrasonic guided wave transducer arrays to rapidly screen large areas of many types of engineering structures for defects by A. Haigh *et al.* [14], use of laser ultrasonics system to detect impact damage in samples of composite material as performed by J. M. S. Sakamoto *et al.* [15]. Moreover, other researcher have developed online defect detection system as done by B. Mi *et al.* [16] whose developed a portable ultrasonic system to automatically inspect tank track shoes for disbond while Silviu Epure *et al.* [17] have describes a fully automated system for measurement of the ultrasonic for a frequency range from 40 to 300 kHz.

Some researcher tend to compare ultrasonic approach with others non-destructive techniques as done by De Angelis *et al.* [18] using a new numerical experimental procedure to detect size and depth of flat bottom holes in metallic and laminated composite structures by digital shearography (DISH). D'Orazio *et al.* [19] in his research inspect composite materials by using automatic analysis of thermography techniques and extracted the information using neural network approach. Besides, B.S. Ben *et al.* [20] used ultrasonic based Lamb waves propagation method for identifying and measuring the damage location in a material for SHM. However, almost all of these study, explain on how to perform and analyse NDT approach on either homogenous or on-homogenous material but not mention on how to develop pulse-echo scanning unit with appropriate specification. Therefore, the development of pulse-echo scanning unit with desirable specification such as portability, cost effective and reliable performance are necessary in order to encourage small medium industry and educational area to involve with this industries.

In this paper, the author have been developed an automated pulse-echo scanning unit with the main objective are the competitive cost, portability and reliable in scanning result. Gantry robot principle being chosen since this mechanism slightly rigid and suitable with composite laminate panel in plane surface. 3 units of bipolar stepper motor type Nema 17 (1.2A) have been use due to its torque performance during operation. Linear motion for x and y-axis are using belting system which is easy to assemble while z-axis is using ball screw type to control the levelness of scanning platform due to rigid and precision of motion control. All these motion were control by microcontroller Arduino UNO R3 with power DC input 5 volts. Single ultrasonic rangefinder 42 kHz as inspection probe have been chosen as preliminary work before proceed for the next future work with high end ultrasonic pulse-echo probe. In this stage, the inspection capability only concentrated on surface defect which is drilling hole with 6 mm in diameter as artificial defect on fiber glass composite laminates due to probe limitation. The arrangement in this paper including introduction in the first section while second section represents the methodology and followed by result and discussion in the third section. The methodology is divided into four parts. First part comprised of a system architecture setup. Next part is a stepping mode setup and followed by scanning speed determination in the third section. Last part is a scanning reliability test.

2.0 METHOD APPROACH

2.1 Overall Process Flow

In this study, there are several process flows that have been achieved starting from the fabrication process to fabricate frame structure, system architecture setup for both motor control parts and data acquisition parts, stepping mode setup for full step mode, half step and micro step mode, scanning speed determination, scanning reliability test repeating scanning operation and finally an overall cost analysis as shown in Figure 1 below. However, fabrication process has been performed at previous work and will not be discussed in this paper as the main objective are focus on scanning reliability and scanning performance by determination of certain parameter in the motor control system using the Arduino program.

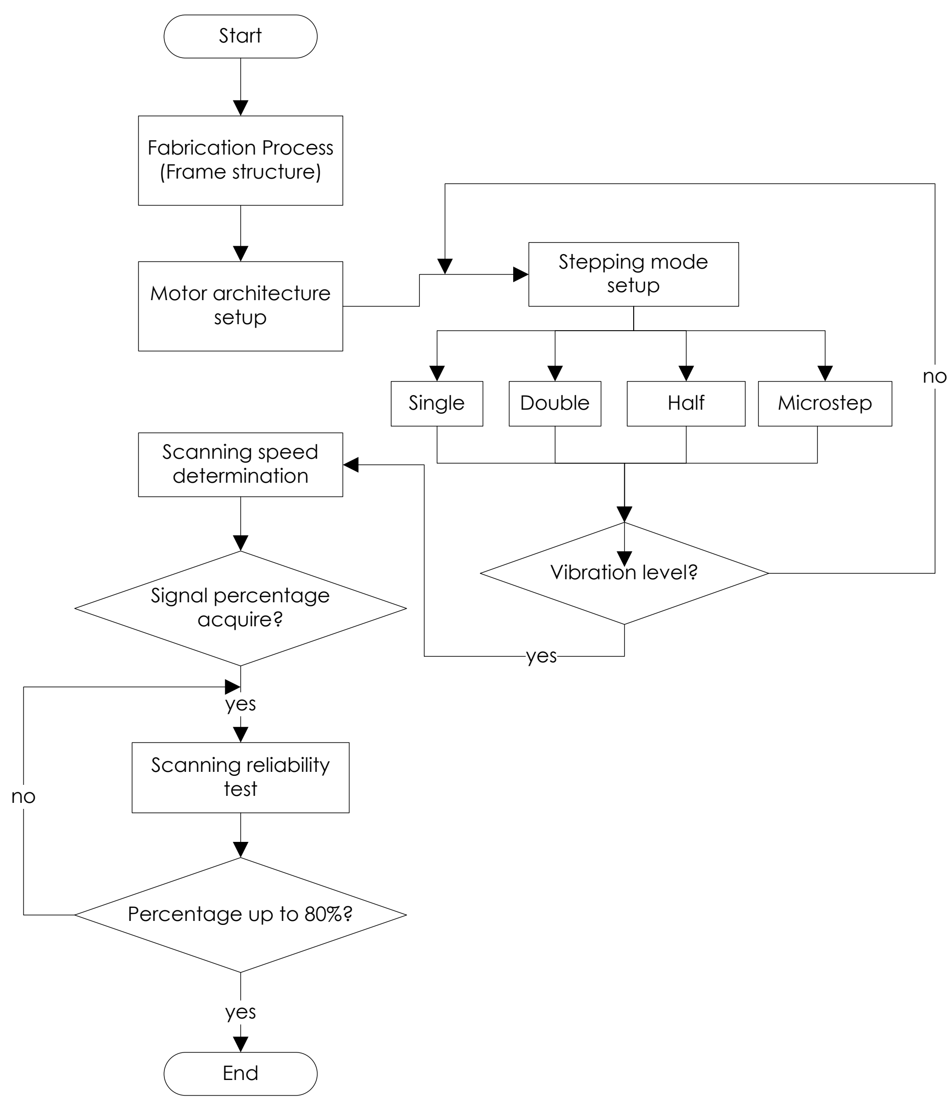


Figure 1 Overall process flowchart

2.2 System Architecture Setup

There are two major system architecture which is a controller and data acquisition as shown in Figure 2 below. Both systems are separately operated using different type of microcontroller. For controller, there are three stepper motor controlled by microcontroller Arduino UNO R3 together with motor driver shield type Adafruit version 2 in order to control motor speed and stepping mode for x, y and z axis linear motion. Hybrid stepper motor type Nema 17, 1.2A and 1.80 step angle has been used due to its torque capability to support overall operation. Since each motor driver shield can connect only two stepper motor, it required two motor driver shield and stacked together with a microcontroller for space reduction and circuit variation. This system architecture is powered by 5 volts DC power supply and connected with a jumper on shield.

Another system architecture is data acquisition where it consists both software and hardware and powered by 5 volts according to computer USB 2.0 hub. It included Matlab software, ultrasonic rangefinder sensor, Arduino Mega 2560 microcontroller and computer to analyze the signal acquired. Ultrasonic rangefinder sensor been used to transmit and receive signals before those signals are sent to the microcontroller. In this phase, the frequency of transmitting signal was up to 42 kHz while the ability sensor to receive the signal are limited up to 20 Hz only. However, it considerable enough as the objective for this is to analyze surface defect on composite laminate. Then, the voltage signal acquired will transfer to Matlab Simulink for real time data acquisition and monitoring. Finally, signal filtering and data recording was performed for further analysis.

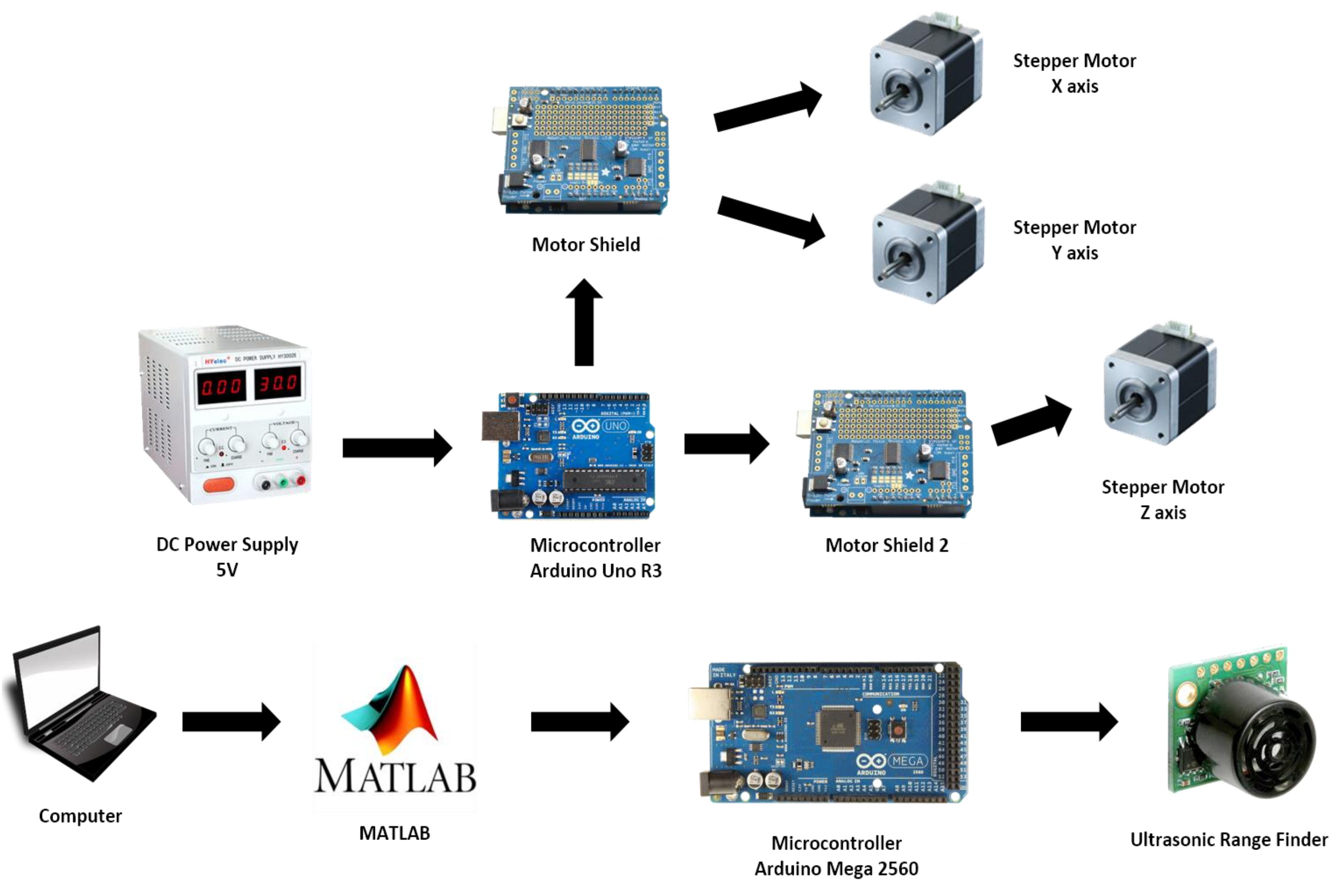


Figure 2 System architecture

2.3 Stepping Mode Setup

Stepping mode setup is necessary in order to ensure smooth linear motion during scanning operation. Poor linear motion during scanning will increase the noise during A-scan signal acquisition and will affect the reliability of data collection. In this study, the author have tested four types of stepping mode which are full step single phase, full step double phase, half step and micro step. The hybrid stepper motor that the author used have 200 rotor teeth and rotate at 1.80 degrees each step. Thus, it complete 200 steps per one revolution. Stepping mode type full step single phase result lower torque as compared full step double phase because single phase is activated in a time and consume minimal power as compared to double phase. As compared to stepping mode type full step double phase, this stepping mode activated two phases in a time and result greater torque than previous stepping mode. Moreover, this mode is more economical instead of energy consumption compared with other. Since stepping mode type full step double phase requires the motor to operate with both phases, it produces greater torque and suitable for high load task.

Another stepping mode is the half step mode where both single and double phase operate alternately to permit step angle at 0.90 degrees. Hence, it increases the motor precision but reduce the torque. Stepping mode type micro step divide each single step into 256 times, resulting 51,200 steps per revolution. This mode causes the motor rotor smoother as compare to the previous stepping mode especially in low speed. It also, reduced resonance effect and produced 30 percent less torque than full step double phase. Vibration test has been performed in order to determine which the most suggested stepping mode for better linear motion performance during scanning operation. Vibration meter model Bruel and Kjaer type 2513 has been used and accelerometer probe is attached at the stepper motor body to acquire data as shown in Figure 3 (a) and 3 (b) below. The motor speed being fixed at 28 RPM as average speed for scanning speed in operation. The vibration result instead of stepping mode setup determination will discuss in result and discussion.

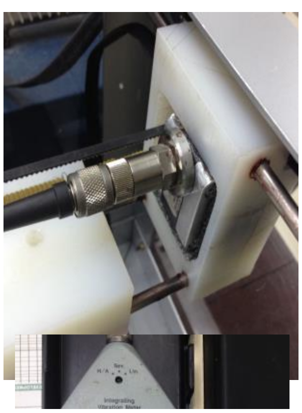


Figure 3 (a)Position of accelerometer (b)Vibration meter reading test

2.4 Scanning Speed Determination

In this study, the author use a hybrid stepper motor to perform linear motion on x, y and z axis. However, the author focused on x-axis linear motion only compared to y and z-axis as this scanning path directly impact the ultrasonic A-scan scanning performance as shown in Figure 4 below. In addition, z-axis linear motion act to control the distance between the transducer and specimen surface. Thus, further analysis on z-axis motion speed is negligible.

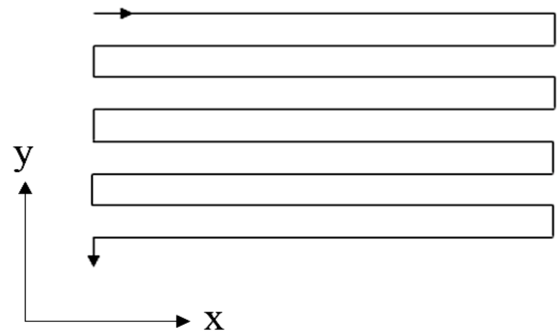


Figure 4 Scanning path

In order to control the scanning speed, a suitable RPM needs to define for better resolution of signal gathered. Several trials have been performed up to 60 RPM in order to develop a trend of scanning speed as guidance for better resolution. Scanning speed can be determined by dividing the total distance region of interest line (ROIL) achieved during the scanning process with total time taken along the scanning path of ROIL. In this study, the author performed scanning speed up to 60 RPM (28.00 mm/sec) whereas the distance of the scanning path along ROIL is 80 mm long for each ROIL. In addition, the frequency during pulse-echo are 42 kHz and 20 Hz respectively. Thus the scanning speed can be calculated using equation (1) below. Equation (2) is used to convert scanning speed into RPM for motor speed control.

$$S = \frac{D_{ROIL}}{t_s} \quad (1)$$

$$RPM = \frac{(S\ x\ 60)}{2\pi r} \quad (2)$$

Where the scanning speed, S is equal to distance along region of interest, DROIL divided by time taken, t_s

2.5 Scanning Reliability Test

In this stage, the author performed two sets of experiment in order to verify the performance of scanning reliability. First, the author compare the A-scan signal between defect and non-defect area along ROIL to ensure the reliability of a transducer to acquire the data as shown in Figure 5. Thus, the data acquire form transducer are not questionable. Secondly, the author compare sets of signal along defective ROIL with idle data using image processing. A 2.4 mm and 6.0 mm thick of fiber glass composite laminates with material properties 430 MPa where getting from flexural test was drilled as artificial defect been used in this scanning inspection. Once the scanned image being processed until binaries image, the total diameter of hole along ROIL of binary image was calculated before divide by total ROIL distance. Finally, the percentage of defects along ROIL for idle condition that is 22.81% been used as reference to determine the scanning reliability.

According to Figure 5 show that the sensor is able to acquire data clearly for both defect and non-defect along selected ROIL. However, the scanning capability of ultrasonic rangefinder limit only surface defect detection due to low frequency pulse-echo specification. The highest peak of signal for non-defective ROIL is 0.06 volts while the highest peak signal for defect ROIL was 0.5425 volts. Signal filtering was carried out in order to filter out noise by using threshold number. Based on program as mentioned before, the threshold value for defect is set to 0.06 volts. Hence, those signals exceed this threshold value are consider a defect and state as 1 while less than that are considered as non-defect which is stated as 0 in Figure 6 below.

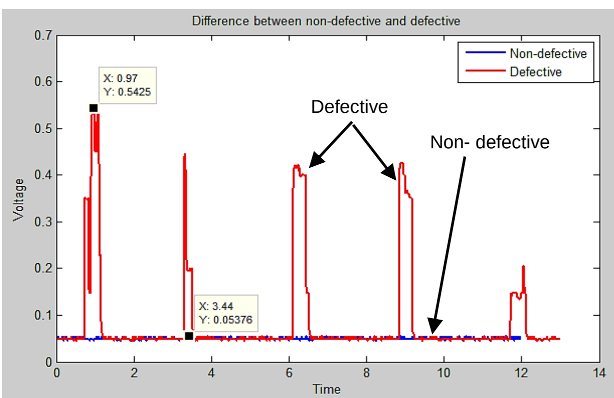


Figure 5 Signal for defect and non-defect along single ROIL

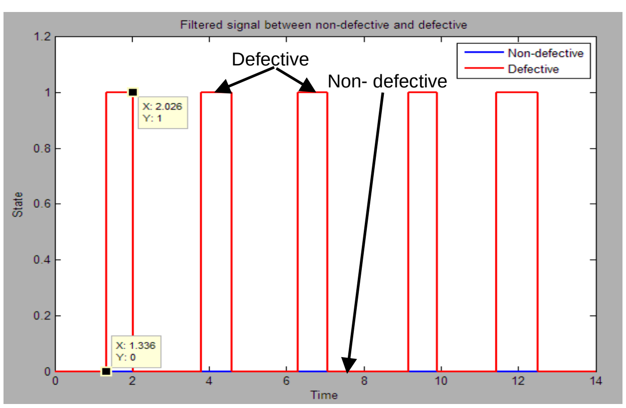


Figure 6 Filtered signal for defect and non-defect along single ROIL

Once the signal filtered, the percentage of defect area along ROIL will take place by using eq. 3 and eq. 4 respectively. Then, the percentage of defect data will be compared through idle data from image processing analysis. This process involved the size of defect through a different percentage of actual and experiment defect's size. However, at this stage the author managed to measure drilled hole which is 6 mm in diameter as artificial defect on laminated composite panel. This process consumed slightly less than 10 sec as performed by low processing method.

Mathematical fraction and percent:

$$\%D_a = \frac{N_{da}}{T_{na}}\ x\ 100 \tag{3}$$

Mathematical Proportion:

$$\frac{L_a}{x} = \frac{T_s}{T_{int}} \tag{4}$$

Where $\%D_a$ = Percentage of defect area, N_{da} = Number of defect area, T_{na} =Total number of area, L_a= actual length, x = size of defect, t_s= time (s) and T_{int} =Time interval in defect area.

The process is repeated several times until the desired results obtained to calculate the yield percentage and difference percentage of defect size. The scanning start with single ROIL for several trials and secondly end up with others ROIL. This activity performed to ensure the transducer in a good condition during data acquisition process. Hence, the signal processing is based on Figure 7 and Figure 8 below where the aim of this effort is to gain yield percentage for signal acquisition during experimental setup. For overall data acquisition process on 60 mm x 80 mm laminated composite panel, it took around 3 minutes to complete this task. However, this scanning speed is depending on frequency rate of transducer that the author are used. Eventually, the author use 42 kHz single ultrasonic rangefinder transducer. Therefore some parameter needs to be compromised before the author proceed into next stage of research.

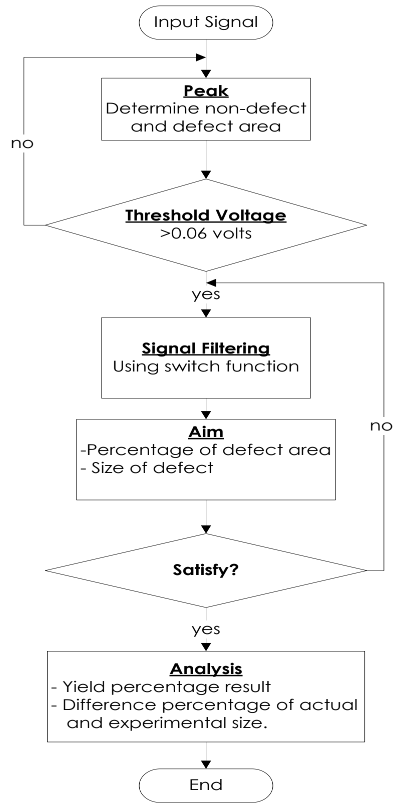


Figure 7 Process flow chart of signal processing

Algorithm 1: Void Percentage

(1) *Input the image signal*
(2) *Select the threshold voltage value > 0.06 V*
(3) *Define perfect = 0; void = 1;*

```
for a:1: length(sample)
  for b=1: length(sample)
    if  sample (a,b)>lower limit &&
        sample (a,b)<upperlimit
            perfect = perfect + 1;
     else
           void=void+1;
    end
 end
 percentage_of_void=((void/length)*100);
 percentage_of_void
```

(4) *Return to step 1 for new loop, depend until satisfy the value.*

Figure 8 Algorithm for signal processing

3.0 RESULTS

3.1 Stepping Mode Vibration Test

In this study, the vibration test result has been used in order to determine which the most suggested stepping mode is during scanning operation. Basically, the lowest vibration rate during scanning operation are considered as the best stepping mode. Over 4 stepping modes involve in this experiment. Since micro step mode produce smooth rotation, it results lowest vibration rate about 120 dB as shown in Table 1 below. The higher vibration rate belongs to full step double phase mode that is 127 dB. In addition, the vibration rate for the half step mode and full step single phase mode are 124 dB and 126 dB respectively.

Therefore, micro step mode is the most suggested stepping modes during scanning operation for smooth and accurate positioning in linear motion application. Moreover, this stepping mode delivers enough torque which is higher than full step single phase mode for scanning operation. Thus, the presence noise during scanning operation can be decrease by minimize the vibration rate for better scanning performance.

Table 1 Stepping mode vibration test

Stepping Mode	Vibration Rate (m/s^2)	Vibration Rate (dB)
Full step (single phase)	200	126
Full step (double phase)	220	127
Half step	170	124
Micro step	100	120

3.2 Scanning Speed

According to the scanning speed experimental analysis that have been done, there are significantly different between signal profile and scanning speed as shown in Figure 9 below. The scanning resolution decrease when scanning speed increase. In this experimental work, several trials on scanning speed determination have been performed up to 60 rpm (28.00 mm/s). The scanning path follows as current ultrasonic scanning machine which is shown in Figure 4 above. At the initial stage, the maximum and minimum value of scanning speed are determined by using try and error method. Then the appropriate scanning speed value is determined after several trial base on signal profile pattern. According to Figure 9 below, scanning speed 30 rpm (12.60 mm/s) are the most suggested value as the distance between two signal peaks that is wider than other that is 2 sec. Thus, the wider the distance between signal peaks result the better scanning resolution for accurate data analysis. However, the scanning speed should not lower than 12 mm/sec because it will increase the noise during scanning operation. Therefore, the proper parameter setup and handling process during scanning operation are necessary in order to get better scanning results.

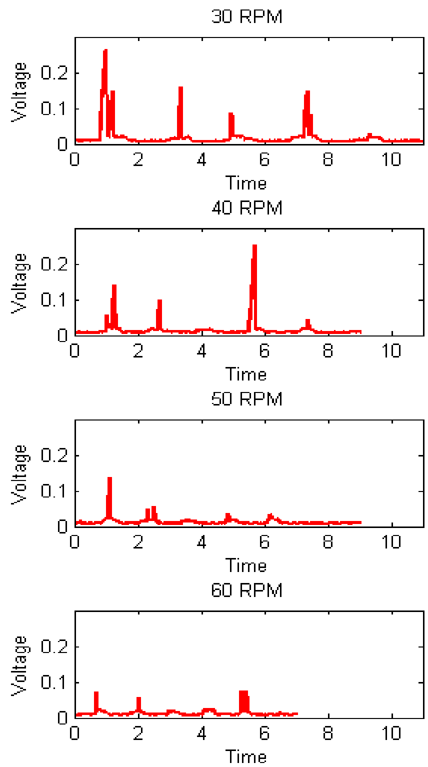


Figure 9 Scanning result with different speed

3.3 Performance of ultrasonic scanning

The scanning performance is crucial in order to provide reliable data. In this study, two approaches have been identified which is repeating the scanning along ROIL which labelled (a) by 10 times to identify the consistency of data acquisition during scanning operation as shown in Figure 10 below. The scanning result of this approach is shown in Table 2 below. The second approach is to scan along ROIL labelled (a), (b) and (c) where the scanning result has been shown in Table 3 below.

In this stage, method I which from index of image pixel is used to compare with method II which is an experimental measurement data is shown in Table. 2 and Table. 3 below. According to Table 1 below, the lowest yield percentage of defects along ROIL is 84.09%, while the highest up to 97.50%. The yield percentage of second approach also greater than 80% where the lowest yield percentage which is 86.54% belong to ROIL labelled (b) and (c) while ROIL labelled (a) is 97.50%.

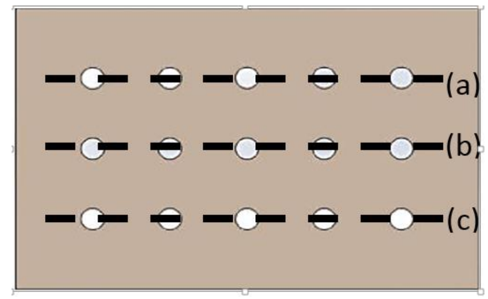


Figure 10 Region of interest line (ROIL)

Table 2 Percentage of defective area along labelled (a)

No. of tests	Percentage of defective area (%)		Yield (%) Method I vs Method II
	Method I	Method II	
1		19.18	84.09
2		19.46	85.31
3		19.33	84.74
4		23.38	97.50
5	22.81	19.18	84.09
6		19.33	84.74
7		20.41	89.78
8		21.89	95.97
9		19.89	87.20
10		23.41	97.37

Table 3 Percentage of defective area along ROIL labelled (a),(b) and (c)

Paths	Percentage of defective area (%)		Yield (%) Method I vs Method II
	Method I	Method II	
a		23.38	97.50
b	22.81	25.97	86.54
c		25.88	86.54

4.0 CONCLUSION

The Pulse-Echo scanning unit are able to inspect surface defect efficiently on fiber glass composite laminates with low scanning speed and using micro stepping mode. From the result, the scanning performance of this scanning prototype are quite stable where the average percentage of different against ten times inspection are as low as 5 percent. In addition, this prototype are applicable to inspect surface defect on fiber glass composite laminates up to 6 mm in thickness. For further research work, the author plan to improve the scanning inspection performance by adding the sound insulation around scanning working space in order to reduce the interference during scanning operation.

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References

[1] W. J. Staszewski. 2002. Intelligent Signal Processing for Damage Detection in Composite Materials. *Composite Science and Technology*. 62(7-8): 941-950.

[2] L. Ye, Y. Lu, Z. Su, and G. Meng. 2005. Functionalized Composite Structures for New Generation Airframes: A Review. *Composite Science Technology*. 65(9): 1436-1446.

[3] C. Garnier, M. L. Pastor, F. Eyma, and B. Lorrain. 2011. The Detection of Aeronautical Defects in Situ on Composite Structures Using Non Destructive Testing. *Composite Structural*. 93(5): 1328-1336.

[4] T. Merazi Meksen, B. Boudraa, R. Drai, and M. Boudraa. 2010. Automatic Crack Detection and Characterization during Ultrasonic Inspection. *Journal Nondestructive Evaluation*. 29(3): 169-174.

[5] J. R. Lee, S. Yenn Chong, H. Jeong, and C. W. Kong. 2011. A Time of Flight Mapping Method for Laser Ultrasound Guided In a Pipe and Its Application to Wall Thinning Visualization. *NDT&E International*. 44(8): 680-691.

[6] T. Hasiotis, E. Badogiannis, and N. G. Tsouvalis. 2011. Application of Ultrasonic C-Scan Techniques for Tracing Defects in Laminated Composite Materials. *Journal of Mechanical Engineering.* 57(3): 192-203.

[7] M. F. Mahmod, M. Z. M. Pauzi, and E. A. Bakar. 2013. Flatbed Scanner Image and Single Ultrasonic Defect Detection. *Proceeding of the IEEE International Conference on Smart Instrumentation, Measurement and Application (ICSIMA) 2013.* Kuala Lumpur, Malaysia. 25-27 November 2013.1-5.

[8] T. Y. Lim, and M. M. Ratnam. 2012. Edge Detection and Measurement of Nose Radii of Cutting Tool Inserts from Scanned 2-D Images. *Optics and Lasers in Engineering*. 50(11): 1628-1642.

[9] C. Meola, and G. M. Carlomagno. 2014. Infrared Thermography to Evaluate Impact Damage in Glass/Epoxy with Manufacturing Defects. *International Journal of Impact Engineering*. 67(2014): 1-11.

[10] W. J. J. Staszewski, S. Mahzan, and R. Traynor. 2009. Health Monitoring of Aerospace Composite Structures - Active and Passive Approach. *Composite Science and Technology*. 69(11-12): 1678-1685.

[11] C. C. Tsao, and H. Hocheng. 2005. Computerized Tomography and C-Scan for Measuring Delamination in The Drilling of Composite Materials using Various Drills. *International Journal of Machine Tools & Manufacture.* 45(2005): 1282-1287.

[12] D. Xiang, G. Zhao, and B. B. Raju. 2010. Automated Ultrasonic Disbond Inspection of Metal Matrix Composite Tank Track Shoes. *Proceeding of American Institute of Physics.* Kingston, Rhode Island, USA. 26-31 July 2009. 1265 -1273.

[13] S. Iyer, S. K. Sinha, M. K. Pedrick, and B. R. Tittmann. 2012. Evaluation of Ultrasonic Inspection and Imaging Systems for Concrete Pipes. *Automation in Construction*. 22(2012): 149-164.

[14] A. Haig, P. Mudge, P. Catton, and W. Balachandran. 2010. Portable Ultrasonic Guided Wave Inspection with Macro Fiber Composite Actuators. *Proceeding of American Institute of Physics*. Kingston, Rhode Island, USA. 26-31 July 2009. 1887-1894.

[15] J. M. S. Sakamoto, A. Baba, B. R. Tittmann, J. Mulry, M. Kropf, G. M. Pacheco, D. O. Thompson, and D. E. Chimenti. 2011. Nondestructive Inspection of a Composite Material Sample Using a Laser Ultrasonics System with a Beam Homogenizer. *Proceeding of American Institute of Physics.* San Diego, California, USA. 18-23 July 2010. 935-941.

[16] B. Mi, X. Zhao, T. Qian, M. Stevenson, C. Kwan, S. E. Owens, B. R. Tittmann, and B. B. Raju. 2007. A Portable Ultrasonic Nondestructive Inspection. *Proceeding of American Institute of Physics*. Portland, Oregon, USA. 30 July – 4 August 2006. 1036-1044.

[17] S. Epure, R. Belea, and D. Aiordachioaie, 2011. On Automated Ultrasonic Measurement System. 2011 *IEEE 17th International Symposium for Design and Technology in Electronic Packaging (SIITME)*. Timisoara, Romania. 20-23 October 2011. 129-132.

[18] G. De Angelis, M. Meo, D. P. Almond, S. G. Pickering, and S. L. Angioni. 2012. A New Technique to Detect Defect Size and Depth in Composite Structures Using Digital Shearography and Unconstrained Optimization. *NDT&E International.* 45(1): 91-96.

[19] T. D'Orazio, C. Guaragnella, M. Leo, and P. Spagnolo. 2005. Defect Detection in Aircraft Composites by Using a Neural Approach in the Analysis of Thermographic Images. *NDT&E International.* 38(8): 665-673.

[20] B. S. Ben, B. A. Ben, K. A. Vikram, and S. H. Yang. 2013. Damage Identification in Composite Materials Using Ultrasonic Based Lamb Wave Method. *Measurement.* 46(2): 904-912.