Development and Experimental Study of Miniature Two-plate Electrical Capacitance Sensor to Detect Dielectric Material

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Abstract*—Electrical capacitance sensing technique is used in many industrial applications. It is being used through the tomography technique in the non-destructive test, process monitoring and control systems and also as proximity sensors. In this paper, electrical capacitance sensor to detect dielectric material has been constructed and experimentally studied. The miniature two plates of electrical capacitance sensor (ECS) is designed using COMSOL Multiphysics software to see the electric field and contour of the electric potential of the system. The capacitance value of the sensor is measured based on AC circuit concept. The alternating current from the sensor flows to the detector circuit providing the voltage corresponding to the capacitance between a pair of electrode. The voltage from the detector has been amplified by amplifier circuit before sending to the lowpass filter to filter out any unwanted signal of the fringe effect. A signal conditioning circuit will process the signal before it is processed by a computer. The LabVIEW software is used as a graphical user interface (GUI) to display the type of dielectric material of paper, plastic or FR4 in the computer system. The experiment process has shown promising results to prove this concept work. When a dielectric material is placed between the parallel plates, each type of dielectric material produces different readings. Furthermore, there are significant results with regards to the size and the permittivity of the object. From the studies, there are two factors that will influence the reading of the sensor, which are the distance between the two sensor plates and the number of electrodes being used on the sensor plates. The results revealed that the sensor can distinguished dielectric material, namely paper, plastic and FR4. These results further support the idea of establishing a parallel plate ECT system to inspect the defect on a composite material. Further work needs to be done to establish whether parallel ECT can distinguish the type of defect which appear on a composite material, such as delamination or crack.

***Index Terms*—Capacitance; COMSOL; Dielectric; Miniature; Sensor.**

I. INTRODUCTION

The Electrical Capacitance Sensor (ECS) is a type of a non-destructive testing technique. This system is adopted from the Electrical Capacitance Tomography (ECT) concept. The fundamental operation of this framework is to quantify the changes of capacitance between terminals which shows the permittivity conveyance and subsequently the material spread between any two adjacent conductors. These two terminals can be considered as a capacitor and different dielectric properties between conductors will create a different capacitance value [1]–[3]. Each of the dielectric material has different permittivity value so it will result in the different capacitance value. Figure 1 shows the overview of the ECS system which consists of three main parts including sensors, data measurement circuit and the processing computer. From the sensors, the data will be acquired by a special circuit which will convert the sensor reading to digital signal [4], [5] before the computer manipulate and display the result. This result may be used for future studies by reconstructing the images of the samples using numerous image reconstruction algorithm namely linear back projection, filtered back projection and iterative methods just to name a few of them [6].

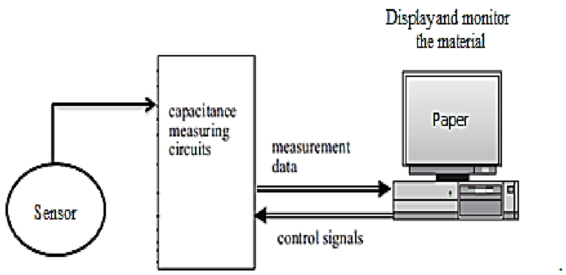


Figure 1: Diagram of ECS System

In addition, the system uses driven guard terminals at both ends of measurement terminals as shown in Figure 2 to enable short measurement terminals to be used [6]. Tomography is one of the important tools which is widely used to perform non-destructive test especially to visualize internal structure of any materials [7]–[9]. For this system, it is non-radioactive, non-intrusive and low cost compare to other it has some advantages over other technique, for example, X-CT and Electrical Resistance Tomography (ERT). In previous papers, ECT has been well described for its applications in industries to measure flow of crude oil in pipelines including flow measurement in oil pipelines [10], [11] wet gas separators, fluidized beds [12]–[14], pneumatic conveyors and gas/solids cyclones [15], [16]. The purpose of the research is to investigate the output voltage corresponding to the capacitance value of the electrical capacitance sensor on dielectric materials test on paper, plastic and FR4 board.

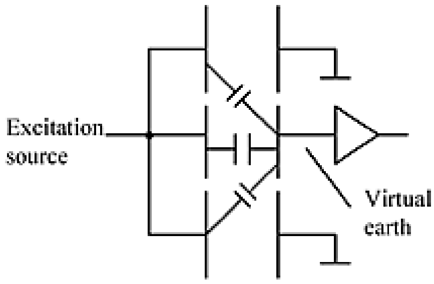


Figure 2: Connection of driven guard electrode.

II. METHODOLOGY

A. *The System Overview*

The block diagram of 2-electrode data collection system for ECS is shown in Figure 3. A signal from function generator drives 500 kHz sine wave excitation voltage of 20 V p-p to an unknown capacitance (capacitance between electrodes of the sensor known as C_x). C_x is connected one side to a stray-immune detector [17]. The capacitance between terminals is obtained based on charges detector method.

The voltage from the detector circuit must be processed first before it is being transferred to the computer. The amplifier circuit is used to amplify the voltage before any interference of the fringe effect can be rejected by the low pass filter circuit. The controller circuit is used to acquire the signal from the low pass filter circuit and display the result on the computer.

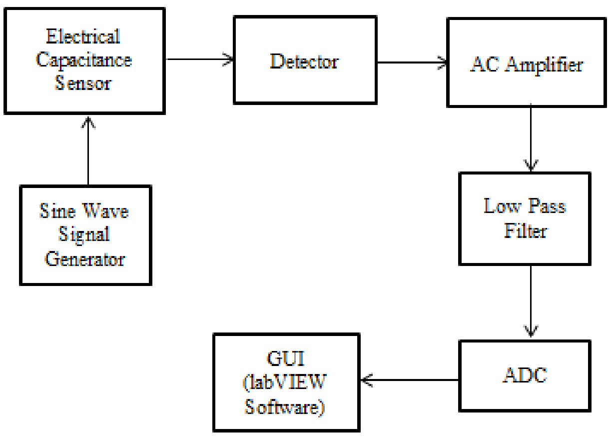


Figure 3: Block diagram of the complete system.

B. *Sensor Model*

The relative permittivity distribution and inter-electrode capacitance can be calculated using Laplace equation, however, it is very difficult to solve the boundary and the geometry conditions [18]. Therefore, COMSOL Multiphysics software has been used to do the Finite Element Method (FEM). COMSOL software has been used to simulate 2D FEM models of two-plate ECS sensors. In the simulation, a sine-wave excitation signal of 20 V peak to peak and 500 kHz is applied to each of the electrodes in turn. In order to suppress any stray noise, the sensor has been insulated and driven guard electrode has also been used [19].

In the simulations, sensor plates are designed to be placed in parallel. The sensors with 2, 4, 6 or 8 electrodes are shown in Figure 4. The design parameters of the sensors are listed as follows.

i. Length of wall: 40mm.
ii. Length of electrodes: 40mm (Sensor 1), 19.5mm (Sensor 2), 12.67mm (Sensor 3) and 9mm (Sensor 4).
iii. Gap between adjacent electrodes: 1mm.
iv. Electrodes material: copper.
v. Material of wall: FR4 (ε_r = 4.8).

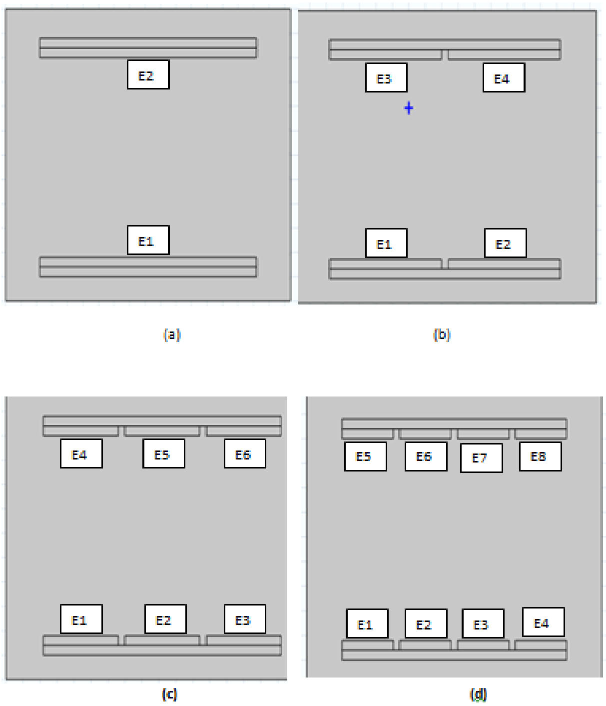


Figure 4: 2D models for parallel two plates ECS sensors. (a) Sensor with 1 electrodes (b) Sensor with 2 electrodes (c) Sensor with 3 electrodes (d) Sensor with 4 electrodes.

C. *Graphical User Interface*

The LabVIEW software was being developed in the system as Graphical User Interface (GUI) as shown in Figure 5. LabVIEW was being interfaced with the controller module to record the analogue inputs and calculate the average capacitance between the electrodes [20].

From the average voltage, LabVIEW will manipulate and display the type of dielectric materials which includes paper, plastic or FR4 in the computer system.

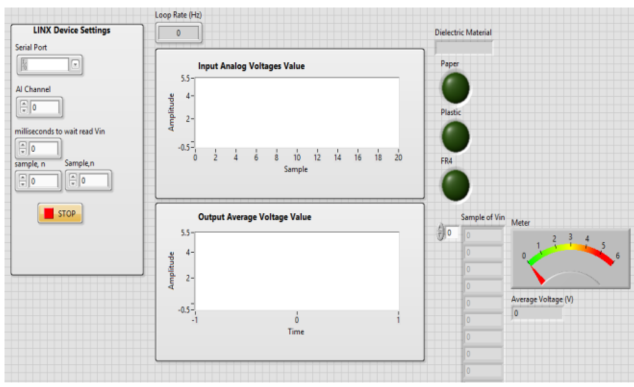


Figure 5: The graphical user interface using LabVIEW

III. RESULT AND DISCUSSION

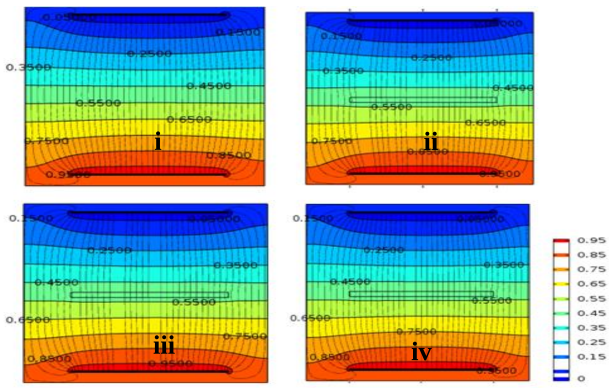
From the experiment, it is found that the capacitance value changes when the distance between two sensor plates is varied. Hence, it also affects the sensitivity distribution. Three distances were selected for simulation: 30, 40 and 50 mm. Figure 6 shows the contours of the electric potential and the electric field lines by two-plate ECS with 2 electrodes, at which the electrode 1 is excited on air, FR4, paper and plastic. The capacitance values with different distance are compared in Table 1.

Table 1
Relationship Between the Dielectric Materials with Capacitance Value

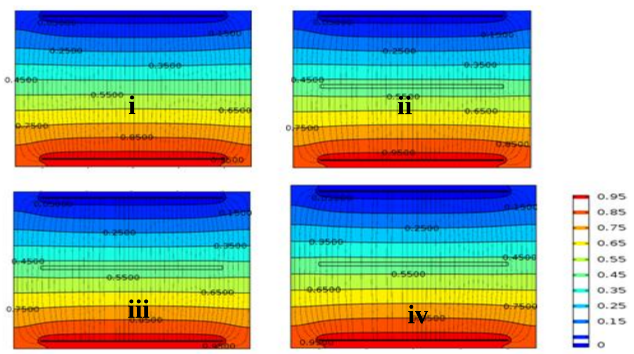
Distance	Material	Capacitance (F)
30 mm	Air	8.5312E-12
	FR4	8.6793E-12
	Paper	8.6662E-12
	Plastic	8.6439E-12
40 mm	Air	6.5077E-12
	FR4	6.5918E-12
	Paper	6.5844E-12
	Plastic	6.5667E-12
50 mm	Air	5.2604E-12
	FR4	5.3184E-12
	Paper	5.3100E-12
	Plastic	5.2985E-12

Table 2
Standing Capacitance of FR4, Paper and Strip Board

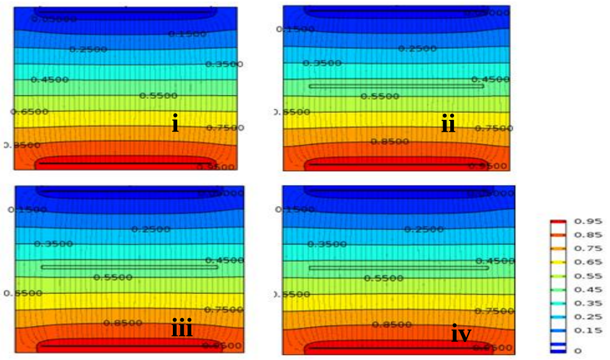
Frequency(Hz)	Material	Capacitance (F)
1K	Air	6.690E-12
	FR4	6.700E-12
	Strip Board	6.680E-12
10K	Air	6.193E-12
	FR4	6.215E-12
	Strip Board	6.196E-12
100K	Air	5.925E-12
	FR4	5.989E-12
	Strip Board	5.928E-12



(a) Distance between two plates = 30 mm



Distance between two plates = 40 mm



Distance between two plates = 50 mm

Figure 6: Contours of electrical potential and electric field lines when electrode 1 is excited on (i) air (ii) FR4 (iii) Paper (iv) Plastic

It can be observed that the smaller distance between the two plates gives the smaller capacitance value and vice versa. It satisfies the concept of the capacitor which shows that the distance between two plates is inversely proportional to the capacitor value. The experiment was carried out when no excitation voltage was injected to the excitation electrode to measure the standing capacitance using LCR meter as shown in Table 2.

As the results, the value of capacitance decreases when the frequency increases. The average voltage of different materials was measured as shown in Figure 7. Each of the material gives different average voltage because of the permittivity value of each material is different.

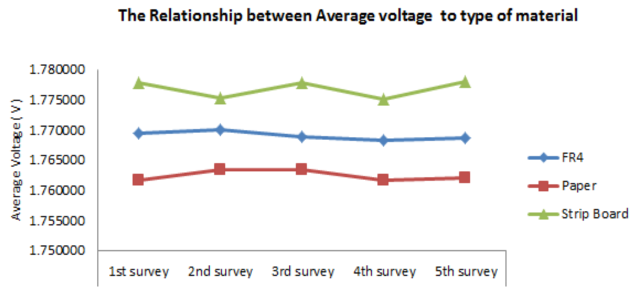
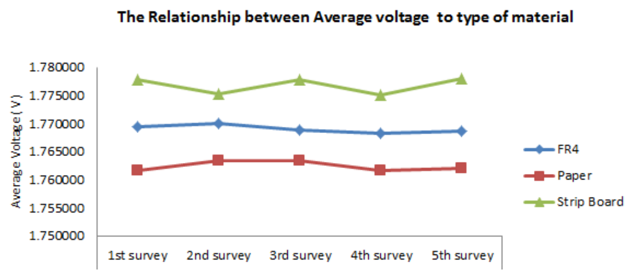


Figure 7: Average output voltage of FR4, Paper and Plastic.

The different distance between the two-plate sensor (15 mm, 20 mm and 35 mm) for each material was being set up. The average voltage for each material is measured and the result is shown as in Figure 8. For all material, the average voltage decreased when the distance between two plates increased.



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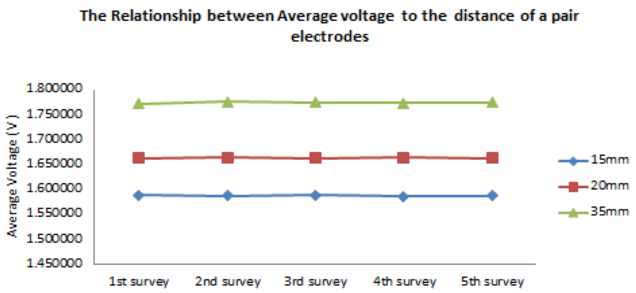

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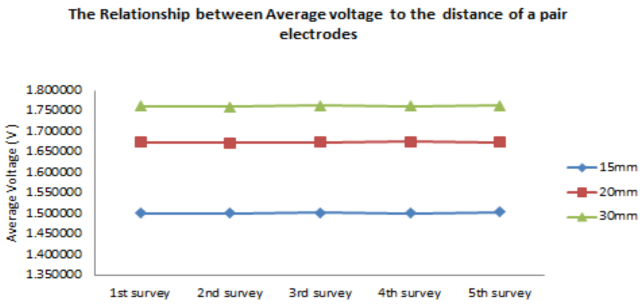

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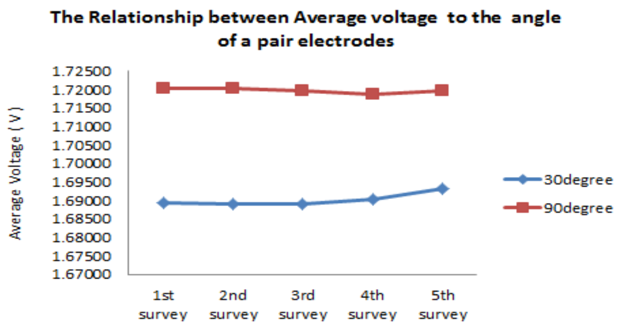
Figure 8: Average output voltage of different distance between two plates. (a) FR4 (b) Paper (c) Stripboard.

From our observation, the value of average voltage for each material is affected when the angle between two plates is being manipulated. The evidence is shown as in Figure 9. As the results, when the angle is increased, the average voltage is also increased.



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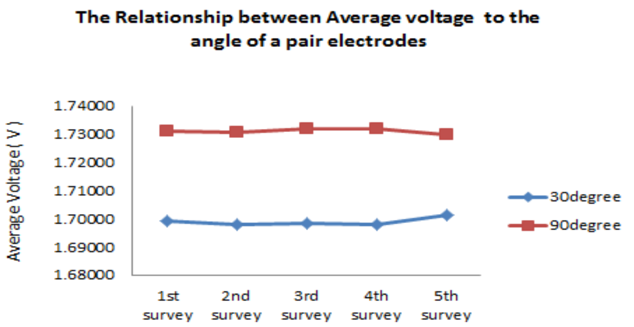

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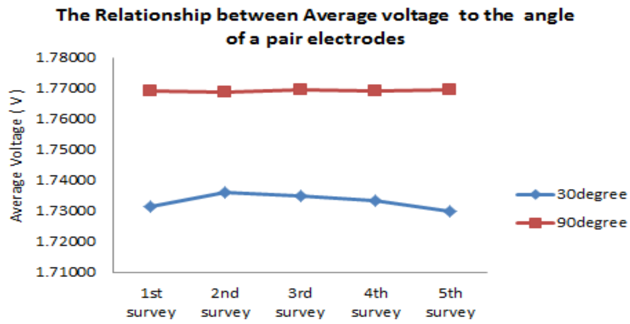

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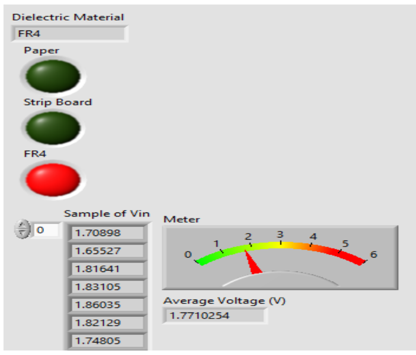
Figure 9: Average output voltage of different angle between two plates. (a) FR4 (b) Paper (c) Stripboard.

Figure 10 shows the LabVIEW is used as monitoring system software to identify the type of material. The output of average voltage which is displayed on LabVIEW corresponds to the capacitance value between two plates of ECS.



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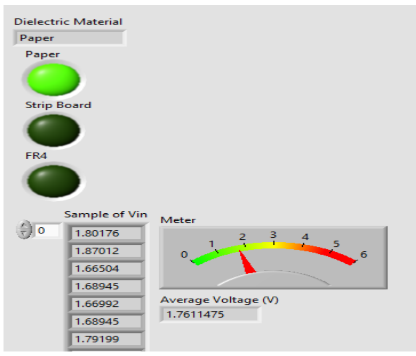

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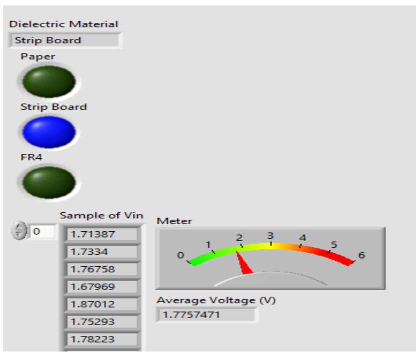

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Figure 10: LabVIEW monitoring the type of material. (a) FR4. (b) Paper. (c) Stripboard

The presented result is obtained via implementation of experimental setup as shown in Figure 11. The experimental arrangement consists of a function generator, electrical capacitance sensor (ECS) that act as sensing element, a detector circuit, amplifier and low pass filter that will perform the signal conditioning before it is being processed by the host computer.

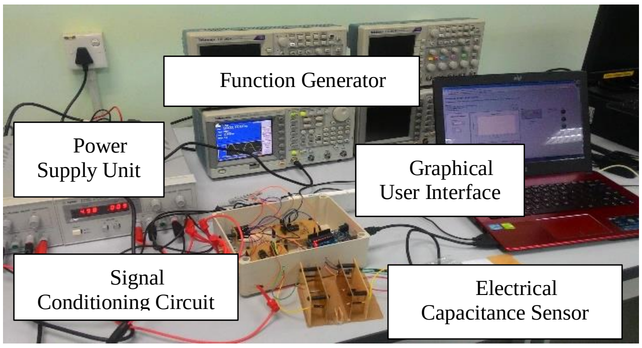
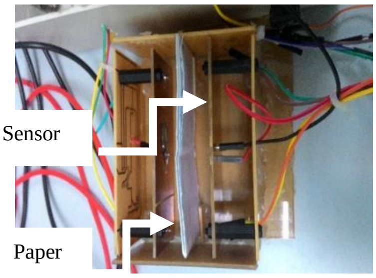


Figure 11: Experiment set up

The experimental setup for measuring the capacitance at a different distance of dielectric materials, standing capacitance at multiple frequency variations and the average output is shown in Figure 12.



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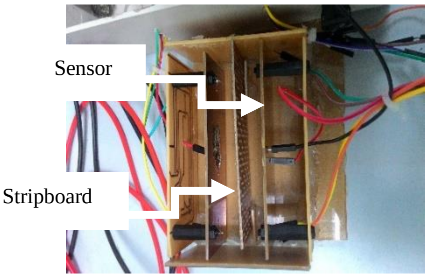

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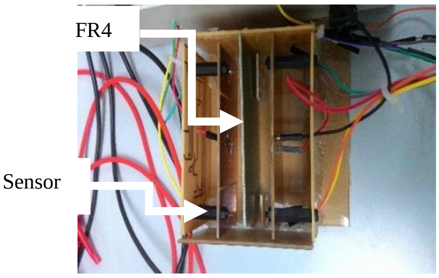

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Figure 12: Material under test by Electrical Capacitance Sensor (ECS) (a) Paper (b) Stripboard (c) FR4

IV. CONCLUSION

From this study, we can summarize that the performance of the two-plate sensor depends on (1) the distance between two plates, (2) the number of electrodes, (3) the angle between two plates. These results support the idea of establishing a parallel plate ECS to check the type of dielectric material. Further studies need to be done in order to make sure whether ECS can distinguish the type of defects which appear on composite material such as delamination, crack, voids and foreign object defect.

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