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A HIGH-SENSITIVITY DIFFERENTIAL CAPACITIVE SENSOR WITH INTEGRATED REFERENCE STRUCTURE FOR VOID DETECTION IN PTFE COMPOSITES

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Keywords: capacitive sensor, void sensor, void defects, polytetrafluoroethylene composites, non-destructive testing, sensitivity optimization.
Abstract. This paper presents a study on the design of a coplanar capacitive sensor for detecting and measuring void sizes in Polytetrafluoroethylene matrix composite plates. To optimize the sensor structure and minimize parasitic components and common-mode noise, the design integrates a reference capacitor and a sensing capacitor with copper electrodes. Simulations were performed to detect voids with radius ranging from 1.1 mm to 1.4 mm and to analyze the sensor's operating principle under various void radius. The simulation results reveal a linear relationship between the output capacitance and the void radius. These findings demonstrate that the proposed sensor has high potential for applications in detecting and measuring void sizes within Polytetrafluoroethylene matrix composite plate.

ВЫСОКОЧУВСТВИТЕЛЬНЫЙ ДИФФЕРЕНЦИАЛЬНЫЙ ЁМКОСТНЫЙ ДАТЧИК СО ВСТРОЕННОЙ ЭТАЛОННОЙ СТРУКТУРОЙ ДЛЯ ОБНАРУЖЕНИЯ ПУСТОТ В КОМПОЗИТАХ НА ОСНОВЕ ПТФЭ

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Ключевые слова: емкостной датчик, датчик пустот, дефекты в виде пустот, композиты из политетрафторэтилена, неразрушающий контроль, оптимизация чувствительности.
Аннотация. В данной статье представлено исследование конструкции копланарного ёмкостного датчика, предназначенного для обнаружения и измерения размеров пустот в пластинах из композитного материала на основе политетрафторэтилена. С целью оптимизации структуры датчика и минимизации паразитных составляющих, а также синфазного шума, в конструкцию были интегрированы опорный и чувствительный конденсаторы с медными электродами. Проведено моделирование, направленное на выявление пустот радиусом от 1,1 до 1,4 мм, а также на анализ принципа работы датчика при различных значениях радиуса пустот. Результаты моделирования демонстрируют линейную зависимость выходной ёмкости от радиуса пустоты. Полученные результаты подтверждают высокий потенциал предлагаемого датчика для применения в задачах обнаружения и измерения размеров пустот в пластинах из композитного материала на основе политетрафторэтилена.

1. Introduction

Plastic composite materials are becoming increasingly attractive in structural applications, particularly in the aerospace industry, due to properties such as high durability and corrosion resistance. These materials can also be tailored to meet precise design requirements and offer significant weight reduction compared to traditional materials like metals. Manufacturing processes are inherently prone to inducing defects in composites, and it is nearly impossible to produce a component that is entirely defect-free, as each process leads to different types of flaws in various ways. Porosity or voids are among the most common manufacturing defects. The presence of voids in composite materials negatively impacts material strength, leading to a severe degradation of mechanical performance [1-5].

Ultrasonic methods have been tested on composite materials to evaluate structures and detect voids [6-7]. Capacitive sensors, known for their high sensitivity and robustness, have become the sensor of choice in many precision measurement applications, including thin-film thickness monitoring, air bubble detection in engine lubricants, and tilt angle sensing. These sensors are preferred due to their low intrinsic noise, minimal sensitivity to environmental variations (e.g., temperature and humidity), as well as their long-term stability and reliability [8-11].

In this study, the research team proposes the design of a capacitive sensor for detecting voids in composite materials. The sensor consists of two capacitors: one serving as the sensing capacitor and the other as the reference capacitor. The electrodes of the capacitors are designed in a spiral shape to enhance the sensor's performance. The study employs theoretical calculations and simulation methods to evaluate the sensor's performance. Voids in the composite material, with radii ranging from 1.1 mm to 1.4 mm, are detected based on the capacitance change between the sensing capacitor's electrode pair. When the composite material contains voids, the dielectric properties of the sensing capacitor are altered, leading to a change in its capacitance. By measuring this variation, the size of the void can be estimated.

2. Theoretical Framework and Sensor Design

The capacitive sensor is composed of two coplanar electrodes separated by a distance (*a*) and placed in a uniform dielectric medium with a dielectric constant ε_r (fig. 1). Figure 1, a shows the cross-section of the coplanar capacitive sensor on a printed circuit board (PCB). The dimensions of the electrodes are defined by their width (*w*) and length (l) (fig. 1, b). The operating principle of this sensor is that placing a composite plate with a dielectric constant (ε_1) (fig. 1, a) underneath the surface of the coplanar capacitive sensor alters the overall dielectric environment beneath the sensor, thereby leading to a change in the sensor's capacitance. When the composite plate is underneath the surface of the sensor surface, two layers – the composite plate, and air can be considered as the new dielectric medium (ε_r). As can be seen in this structure, the dimensions and the gap between the electrodes remain constant. This sensor detects the dielectric medium underneath the surface of the electrodes. The electric field is stronger in the region near the gap between the two electrodes and weakens as it moves outward. A capacitor with two coplanar electrodes placed in an environment with a dielectric constant of ε_r (fig. 1a) has a capacitance determined according to the formula (1) [12]:

$$C = \frac{2\varepsilon_r \varepsilon_0 l}{\pi} \ln\left[\left(1+\frac{2w}{a}\right)+\sqrt{\left(1+\frac{2w}{a}\right)^2-1}\right], \qquad (1)$$

where ε_0 is the vacuum dielectric constant, l is the length (along the z axis) and w is the width of the electrode. The gap between the two electrodes is a (fig. 1, b).

Capacitive sensors are capable of detecting changes in capacitance relative to the dielectric constant. In this paper, a two-electrode capacitive sensor is used to detect the presence of voids in a composite plate.

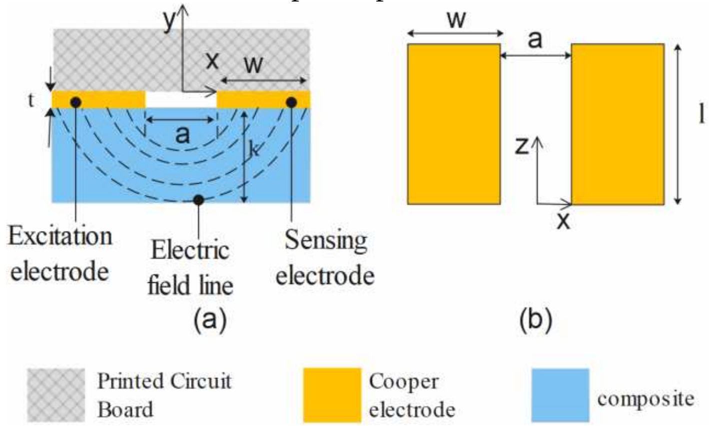


Fig. 1. Positioning of the excitation and sensing electrodes

Figure 2 illustrates the structure of the sensor, demonstrating a capacitive sensor configuration with two capacitors: a sensing capacitor and a reference capacitor. The reference capacitor is placed on a non-voids composite plastic plate, generating a capacitance denoted as C_1. Meanwhile, the sensing capacitor is placed on a similar composite plastic plate but with viods, resulting in a capacitance denoted as C_2.

The differential capacitance ΔC between the reference capacitor C_1 and the sensing capacitor C_2 varies linearly with the size of the void within the composite plastic plate placed on the sensing capacitor. This difference ΔC is calculated as follows:

$$\Delta C = \left| C_1 - C_2 \right| \tag{2}$$

The differential capacitance (ΔC) between the reference capacitor (C_1) and the sensing capacitor (C_2) is estimated based on the output voltage (see fig. 3). The value of ΔC can be determined from the amplitude of the output sine wave.

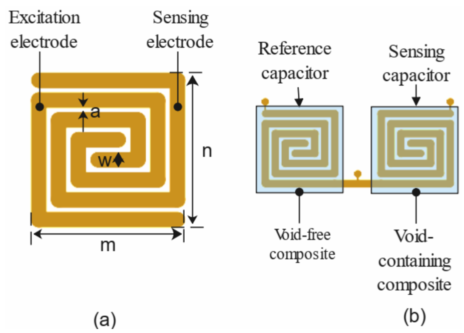


Fig. 2. Description structure of the capacitive sensor

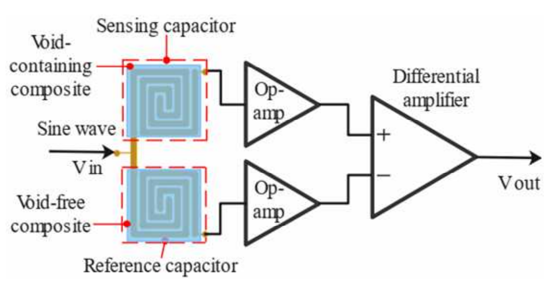


Fig. 3. Circuit converts the difference in capacitance to voltage

Tab. 1. Dimensions of sensors

Symbol	Quantity	Unit (mm)
a	Gap distance between electrodes	0.25
w	Electrode width	1.03
t	Electrode thickness	0.1
n	Width of the sensors	9.99
m	Length of the sensors	9.99

Table 1 presents the dimensional specifications of the capacitive sensor shown in Figure 2.

3. Simulations and Discussion

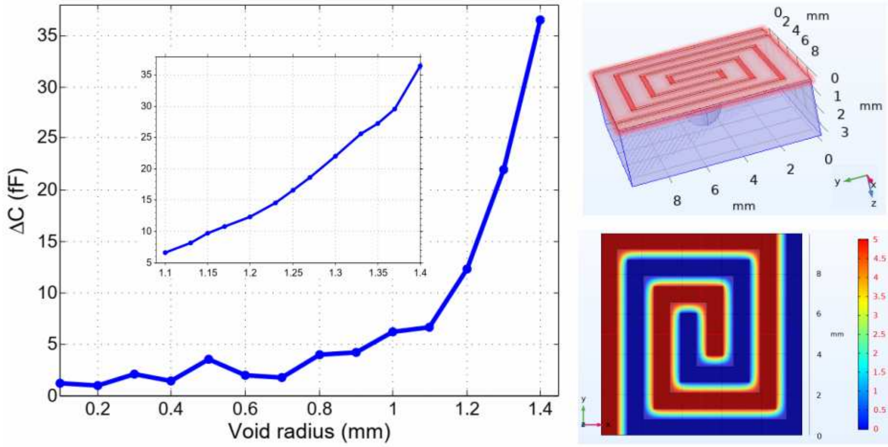
In this study, Comsol Multiphysics simulation software was employed to evaluate the sensor's performance. The electric field distribution within the sensor was analyzed by applying a voltage of 5 V between the excitation electrode and the sensing electrode. The sensor parameters were designed as outlined in Table 1. The simulated material parameters used in the model are summarized in Table 2. The Polytetrafluoroethylene (PTFE) matrix composite plate used in this simulation has a thickness of 3 mm.

Tab. 2. Simulation parameters in the model.

System component of the sensor	Material	Dielectric constant	Conductivity (S/m)
Air	Air	1	-
Composite plastic	PTFE matrix Composite	2.2	10^{-16}
PCB	FR4	4.1	-
Electrode	Copper	-	$5.96 \cdot 10^{7}$

The simulation results in figure 4, a shows the relation between output capacitance changes and investigated voids size in a PTFE matrix composite. This simulation result shows that when the voids size in a PTFE matrix composite changes from 0.1 mm to 1.4 mm, the output capacitance changes correspondingly from 1.2 fF to 36.5 fF. It can be assumed that within a small range, where the voids radius varies from 1.1 mm to 1.4 mm, the relationship between the voids radius and capacitance is approximately linear. The sub-figure in Figure 4, a shows the linear fit of the capacitance values relative to the sensor's pore radius measuring range of 1.1-1.4 mm. In this range the sensitivity achieves 99.66 fF/mm.

Figure 4, b illustrates the electrostatic field when a composite plate is placed under the electrodes and simulated image of the sensor. The red regions represent higher voltage, while the blue regions indicate lower voltage. This electric field distribution demonstrates a significant influence between the sensing electrodes and the composite plate.



a) b)

Fig. 4: The output capacitance changes corresponding to the voids size varying and simulated image of the sensor

4. Conclusions

This study introduces a spiral-structured capacitive sensor designed for measuring void sizes. The proposed sensor has a length and width of 9.99 mm, an electrode width of 1.03 mm, and a gap width of 0.25 mm. To optimize performance, a reference capacitor structure was integrated to minimize noise, enhancing measurement accuracy and stability. Specifically, two capacitive sensors are integrated directly on the same PCB to effectively mitigate power supply noise, parasitic capacitance, and moisture absorption of the PTFE matrix composite. The presence of voids in the composite plate alters local dielectric properties, resulting in a measurable change in the sensor's capacitance. The proposed sensor exhibits a sensitivity of 99.66 fF/mm. Simulation results demonstrate that this sensor structure is cost-effective, highly sensitive, and well-suited for applications involving the detection and measurement of void sizes in PTFE matrix composite.

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