DOI 10.5162/EUROSENSORS2025/SP2.4

Real-Time Monitoring of Cracks in Carbon Fiber-reinforced Polymers under Bending Vibrations with Piezoelectric Composite Sensors

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Summary:
Detecting defects in carbon fiber reinforced polymers (CFRP) used in aircraft is time-consuming and costly, increasing maintenance burdens and affecting safety. This study proposes a real-time crack detection method by laminating KNN-epoxy composite onto CFRP and analyzing its electrical response during bending vibration. Vibration tests revealed that cracks cause a decrease in resonance frequency and output voltage, while rectified AC voltage stored in a capacitor enabled wireless transmission for crack detection via time delay, demonstrating the system's potential for real-time CFRP monitoring to improve safety and efficiency.

Keywords: Structural Health Monitoring, Carbon fiber-reinforced polymer, Piezoelectric composites, Potassium sodium niobate, Crack detection sensors

Background

In recent years, as the cruising range of aircraft has increased, there has been an increasing demand for improved fuel efficiency and safety. Carbon fiber-reinforced polymers (CFRP), which have a high specific strength [1], are attracting attention as a material for aircraft bodies. However, detecting internal defects in CFRP is difficult, causing problems such as reduced safety and increased maintenance burdens.
This study proposes a method for real-time defect detection in CFRP using piezoelectric composite materials. The aim was to detect internal cracks using the electrical signals generated by piezoelectric materials, using vibrations during aircraft operation. In particular, we focused on potassium sodium niobate (KNN), which can be used over a wide temperature range [2], and created a piezoelectric composite material with improved flexibility by mixing it with epoxy resin [3]. Furthermore, a bending vibration test was conducted using samples in which the length of the interlayer cracks was varied by laminating this material onto CFRP. Its power generation performance was evaluated, and it confirmed that the power generated could be used as a power source for data transmission. Based on the above, we showed that the CFRP and KNN-epoxy specimen (CFRP/KNN-epoxy) is a promising self-powering defect detection sensor.

Preparation of specimens

KNN particles were mixed with epoxy resin at a volume fraction of 30% to create a composite material (KNN-epoxy) with an optimized balance of piezoelectricity and flexibility. Furthermore, this material was laminated with two sheets of CFRP prepreg to create four types of specimens with cracks of 0, 5, 10, and 15 mm between the CFRP and KNN-epoxy layers [4].

Experimental method

One end of CFRP/KNN-epoxy was fixed and attached to a vibration machine to apply bending vibration in the thick direction. The voltage generated at that time was recorded, and the relationship between the length of the interlayer crack, resonant frequency, and output voltage was investigated. Furthermore, the alternating current (AC) voltage generated was connected to an Internet of Things (IoT) kit, which includes a rectifier and a capacitor for wireless communication, and the transmission interval was measured.

Results and Discussion

Using a vibration machine, we applied vibrations of 150 to 350 Hz to four types of CFRP/KNN-

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epoxy specimens and measured the amplitude of the generated voltage (Fig. 1). As a result, the CFRP/KNN-epoxy without a crack resonated at 262 Hz, and a maximum voltage of 13.6 V was recorded. On the other hand, as the length of the interlaminar crack increased, the resonance frequency decreased, and a trend of accompanying voltage amplitude decreasing was confirmed. In the specimen with a crack length of 15 mm, the resonance frequency decreased by 8 Hz, and the voltage amplitude decreased by approximately 6 V at maximum. In addition, when comparing specimens with different crack lengths, a certain relationship was observed between the change in resonance frequency and the decrease in voltage output. It suggests that by analyzing the resonance characteristics of CFRP/KNN-epoxy, it is possible to quantitatively evaluate the presence of interlaminar cracks and their length.

Furthermore, to evaluate the power generation characteristics and energy storage performance of CFRP/KNN-epoxy, an experiment was conducted to utilize the generated power by connecting it to the IoT kit. The capacitor built into the transmitter charges over time, and when the voltage reaches 1.4 V, radio waves are transmitted (Fig. 2). As a result of the measurements, it was found that in the crack-free specimen, the first transmission was confirmed after 3059 s, but in the specimen with an interlayer crack, as the crack length increased, the charging rate of the capacitor decreased. It became clear that the interval between wireless communication increased. In particular, the transmission interval increased significantly in the specimen with a 15 mm crack, confirming that the effect of interlaminar cracks on energy conversion efficiency is significant. In addition, the observed correlation between the change in transmission interval and crack length demonstrates that real-time monitoring of interlaminar cracks in CFRP is feasible by utilizing the energy harvested from the CFRP/KNN-epoxy.

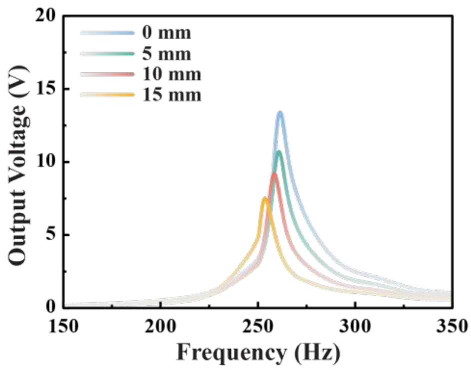

Fig. 1. Impact of different crack lengths on the output voltage and resonance frequency.

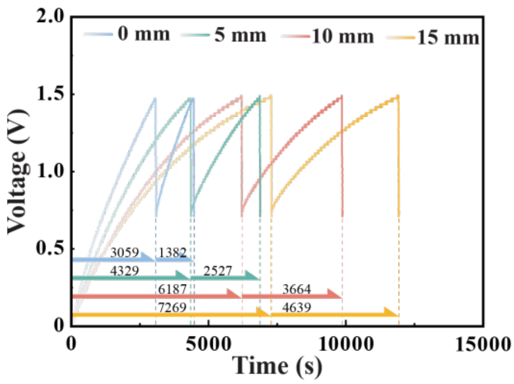

Fig. 2. Transmission interval of the IoT kit's radio waves.

Conclusion

In this study, a CFRP/KNN-epoxy laminate was fabricated, and its piezoelectric properties and defect detection performance were evaluated. The CFRP/KNN-epoxy showed high piezoelectric performance, and an output voltage of 13.6 V was obtained at a resonance frequency of 262 Hz. Furthermore, the effect of interlayer cracks on the resonance frequency and voltage amplitude was analyzed, and a decrease in frequency and voltage corresponding to the length of the crack was confirmed. In addition, the energy storage performance of CFRP/KNN-epoxy was evaluated, and it was shown that it was possible to supply sufficient power for LED lighting and wireless communication. From the above, this material can be expected to be applied as a defective detection sensor that does not require an external power supply.

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