

WIRELESS DAMAGE DETECTION OF CFRP USING SELF-ANTENNA TECHNOLOGY

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SUMMARY

Wireless structural health monitoring (SHM) techniques generally rely on the integration of sensors, transmitters, and antennas into structures; however, the ideal solution would entail the material itself acting as a monitoring system. The current work investigates the application of antenna/sensing multifunctional composites. In this technique, carbon fiber reinforced plastic (CFRP) structures are modeled as half-wavelength dipole antennas. The electrical or antenna property varies in accordance with damage occurrence and can be monitored wirelessly at a remote location. The feasibility of wireless SHM using the self-sensing antenna technique is investigated analytically and experimentally using unidirectional CFRP laminates. The CFRP radiates radio energy well when it is used as a half-wavelength dipole antenna, and damages to the CFRP can be wirelessly detected by monitoring an increase in the resonant frequency of the CFRP antenna.

Keywords: Multifunctional composites, Smart structures, Electrical properties, Wireless.

1. INTRODUCTION

In recent years, researchers have addressed the possibility of designing antennas that fulfill electrical as well as mechanical requirements and form the basis for composite antenna design. Conformal antenna arrays that are integrated into the composite skin of an aircraft have been proposed and demonstrated within the Smart-Skin Structure Technology Demonstration (S³TD) program [1, 2]. Popular solutions for the load-bearing antenna system are the conformal load-bearing antenna structure (CLAS) [3-6], the composite smart structure [7, 8], and the surface antenna structure [9]. In a CLAS, a strip antenna is sandwiched between layers of Nomex honeycomb, which are then laminated with glass fiber reinforced plastic layers, resulting in a planar antenna structure that has a high bending stiffness and is conformal to shell surface designs such as aircraft wings or automobile roofs. The CLAS design, however, relies on traditional metallic materials for the electrically active radiating element. The surrounding Nomex and composite layers are essentially packaging materials that give structure to and protect the antenna element, but the electrical and structural properties are not integrated. In addition to the problem of antenna integration, SHM techniques generally rely on embedding sensors into structures [10, 11]; however, the ideal solution would entail the material itself acting as a monitoring system.

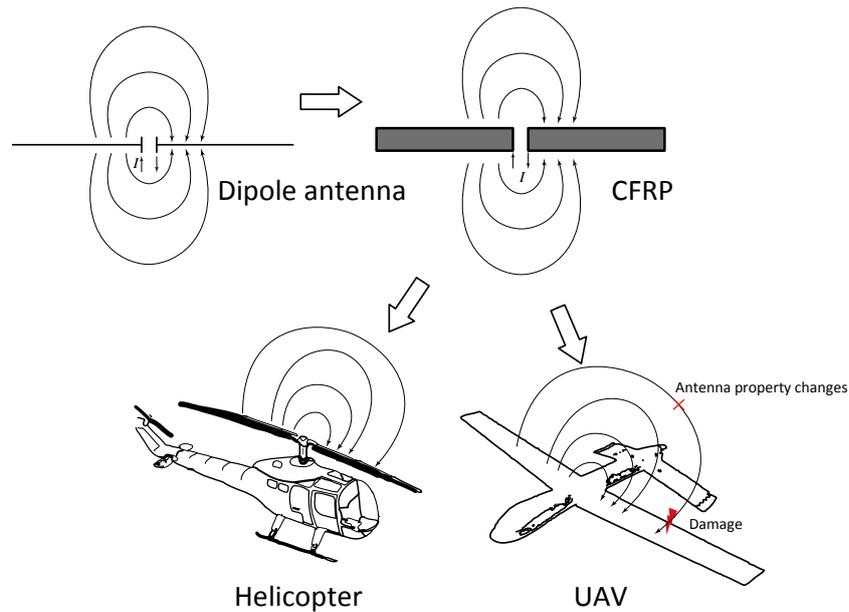


Fig. 1 Evolution of antenna configurations from a dipole to antenna/sensor multifunctional wing structures.

In previous studies [12, 13], we used carbon fiber itself as a sensor in carbon fiber reinforced plastics (CFRPs) for the wireless monitoring of applied strain, fiber breakage, and delamination. The method uses a voltage-controlled oscillator to convert the change in the electric resistance of the CFRP structures due to damage to changes in the oscillating frequency. The proposed method was applied to CFRP laminates, and oscillating frequencies at multiple locations were measured wirelessly in real time. However, many resistance–voltage converters and transmitting antennas are required to cover whole structures.

The present research realizes antenna/sensor multifunctional composites for the wireless detection of damage to CFRP structures. Using the high electrical conductivity of carbon fiber, the CFRP structures can be modeled as antennas and sensors in addition to having load-bearing capability. The electric properties of CFRP structures vary in accordance with damage such as fiber breakage or delamination; damage also affects the properties of the CFRP antenna. This change in the antenna property due to damage can be observed wirelessly at a remote location, and it provides information on the damage. Since CFRP acts as an antenna and sensor, a fully integrated load-bearing wireless SHM solution can be realized. In the present study, unidirectional CFRP composites are used as antenna materials. The feasibility of wireless SHM using the antenna/sensor multifunctional technique is investigated analytically and experimentally.

2. ANTENNA/SENSOR MULTIFUNCTIONAL COMPOSITES

2.1 Concept

There are a number of different antenna configurations that can be used for a CFRP antenna prototype. The most basic is a dipole antenna, which is traditionally made by suspending two wires with an insulator connecting their ends to one another. One end of the dipole has a current feed, and the opposite end is grounded. Since carbon fibers of CFRP have high electrical conductivity, a CFRP blade or wing structure may also act as a dipole antenna when electrical current is fed to the ends of the blade structures. The concept of a full antenna wing or blade structure is shown in Fig. 1. One end of the wing

has a current feed, and the other end is grounded, producing the electrical field shown. If there is serious damage such as fiber breakage, the antenna properties of the CFRP may change. The damage can then be detected wirelessly by evaluating the change in the antenna property. Moreover, by installing current feed cables to the ends of each wing, the whole area of the wings, which function as antennas, can be monitored. Since this method eliminates conventional structural cutouts, antenna joining, and sensor integration, and improves structural efficiency, most air vehicles could benefit from the proposed multifunctional composite technology.

2.2 Self-sensing using the change in the antenna property

A half-wavelength dipole is a balanced antenna comprising two radiators that are each a quarter-wavelength. The voltage in the antenna element changes sinusoidally, and the feed point is at a voltage minimum and a current maximum. The voltage wavelength λ is expressed as

$$\lambda = \frac{c}{f_0}, \quad (1)$$

where f_0 is the resonant frequency and c is the speed of light, 3.0×10^8 m/s. The length of the half-wavelength dipole antenna l corresponds to the half wavelength ($l = \lambda/2$). The resonant frequency can be written using the antenna length l as

$$f_0 = \frac{c}{2l}. \quad (2)$$

From Eq. (2), the resonant frequency is determined by its length. However, there is an imaginary part (reactance) associated with the input impedance of a dipole Z_L , and the total impedance for $l = \lambda/2$ is [14]

$$Z_L = 73 + j42.5. \quad (3)$$

To reduce the imaginary part of the input impedance to zero, the antenna is matched or reduced in length until the reactance vanishes. Usually the length of the dipole for the first resonance is about $l = 0.47$ to 0.48λ depending on the radius of the wire. Note that even for the same element length, the resonant frequency can be adjusted; inductors connected to the antenna decrease the resonant frequency whereas capacitors increase the resonant frequency.

Since there are both reflected and incident waves, the antenna impedance Z_L is expressed as [15]

$$Z_L = \frac{V_{inc} + V_{ref}}{I_{inc} + I_{ref}} = \frac{V_{inc} + V_{ref}}{\frac{V_{inc}}{Z_0} - \frac{V_{ref}}{Z_0}}, \quad (4)$$

where V_{ref} is the reflected voltage, V_{inc} is the incident voltage, I_{inc} is the incident current, I_{ref} is the reflected current, and Z_0 is the characteristic impedance of the line.

A signal traveling down a conductor reflects at the antenna length and a frequency mismatch occurs. The reflection coefficient Γ is defined as the ratio of the reflected voltage to the incident voltage, and it is expressed using Z_L and Z_0 from Eq. (4) as

$$\Gamma = \frac{V_{ref}}{V_{inc}} = \frac{Z_L - Z_0}{Z_L + Z_0}. \quad (5)$$

The reflection coefficient Γ varies from -1 to $+1$, depending on the magnitude of the reflection. The return loss RS is the magnitude of the reflection coefficient in decibels and is expressed

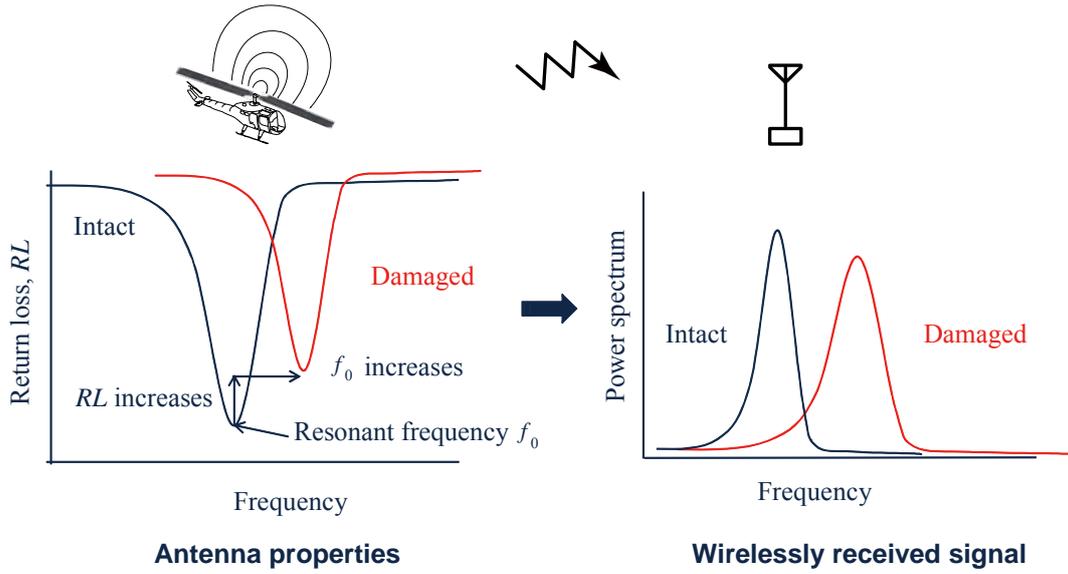


Fig. 2 Schematic diagram for antenna/sensor multifunctional composites that use changes in the antenna property.

as

$$(RL)_{dB} = 20 \log_{10} |\Gamma|. \quad (6)$$

If the antenna does not emit radio waves, the return loss RL is equal to zero, whereas if it perfectly emits radio waves, the return loss is negatively infinite. Since the return loss is a minimum at the resonant frequency, it is often used for resonant frequency estimation.

Next, let us consider the electric current applied to CFRP structures. Since CFRP is a conductive material, the structure may radiate radio waves and can be modeled as an antenna. Its resonant frequency f_0 depends on the length of the structure according to Eq. (2). When damage occurs within the structure and the electric current distribution in the CFRP changes, the antenna properties may also change; that is, since the damage interrupts the electric current path, as the modeled element length decreases, the corresponding resonant frequency increases. Thus, by measuring the resonant frequency shift from the intact state, the location of the damage can be estimated. Moreover, if the antenna impedance Z_L in the intact state matches the line impedance Z_0 , then Z_L differs from Z_0 because of the damage, and RL at the resonant frequency increases. This change in the antenna impedance Z_L can also be estimated using RL from Eqs. (5) and (6). Using the schematic diagram presented in Fig. 2, the relationship between the frequency and return loss RL tells us of damage occurrence and provides other information such as the location of the damage or the magnitude of the impedance change. In practical use, CFRP structures are used as transmitting antennas, and the power spectrum of radio waves received from such structures could be an indicator of structural health.

3. ANTENNA/SENSOR MULTIFUNCTIONAL COMPOSITES USING UNIDIRECTIONAL CFRP LAMINATES

3.1 Damaged antenna simulation

Using antenna simulation software, resonant frequencies are calculated for damage in one element. We used a full-wave, method-of-moments-based electromagnetic simulator, IE3D (Zeland Software, Inc.). The element model of a dipole antenna is 180

mm in length, 20 mm in width, and 1.6 mm in thickness. Each element is located at a distance of 5 mm, and the feeding points are located at the ends of the elements. Isotropic conductivity is used for simplicity. Note that electric current only flows in the longitudinal direction and not in the transverse direction, and electrical conductivity in the transverse direction does not greatly affect the antenna performance. The damaged antenna is modeled by shortening the element length, simulating that the electrical current is interrupted owing to fiber breakage.

Fig. 3 shows the return loss RL vs. frequency, with the length of one element shortened from 180 to 120, 80, and 20 mm to simulate antenna damage. The element length of 180 mm indicates the intact condition, while a shortened element length indicates fiber breakage at that distance from the feed point. In case that the elements are intact, the return loss has a minimum at the resonant frequency of about 390 MHz, which agrees with the frequency calculated using Eq. (2) considering the reactance effect for $l = 0.47 \lambda$. As the element is shortened, the resonant frequency increases as shown in Fig. 3. In addition, an increase in the return loss, or a decrease in the dip magnitude, is also observed. This indicates that the antenna radiation ability decreases because the antenna is not an ideal half-wavelength dipole antenna.

From this simulation, we can estimate damage occurrence by detecting a shift in the resonant frequency or magnitude of the return loss. Moreover, from the shift in the resonant frequency, we can estimate the length of the damaged element by referring to the simulation results as shown in Fig. 3. The changes in the return loss property also lead to peak shift or reduction of the power spectrum of the signal wirelessly received from the CFRP antenna structure. However, the magnitude of the peak of the power spectrum is also affected by conditions of the wireless transmission environment such as the wireless range, output power, and weather conditions. Thus, the resonance frequency shift should be used for the detection of damage and estimation of its location.

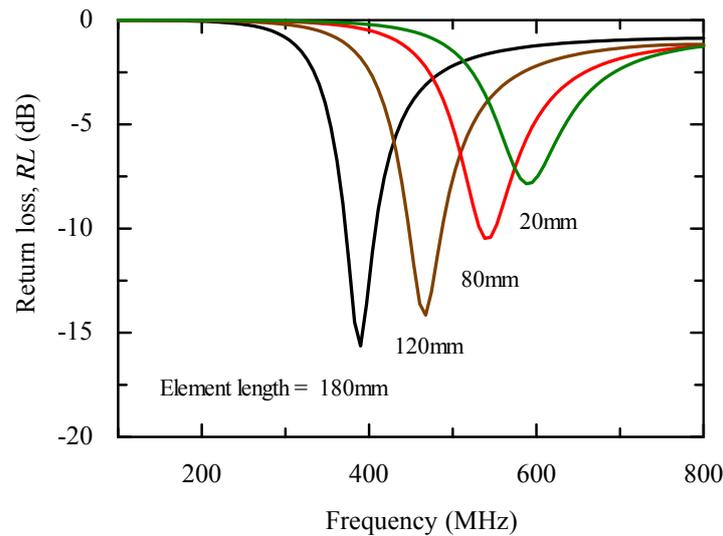


Fig. 3 Simulated frequency response of the return loss RL to changes in the element length.



Fig. 4 Experimental setup for wireless damage detection tests. CFRP is used for the transmitting antenna while an aluminum dipole is used as the receiving antenna. The distance between the two antennas is set to 1 m in the experiments.

3.2 Experimental procedures

Laminated CFRP rectangular specimens are fabricated using Pyrofil 380, a carbon/epoxy prepreg produced by Mitsubishi Rayon Co. Ltd. The stacking sequence of the laminates is $[0_7]_T$, where zero degrees indicates the longitudinal direction. The curing temperature is 130°C , the curing time 90 min, and the curing pressure 0.7 MPa. The specimen is 180 mm in length, 20 mm in width, and 1.6 mm in thickness. To feed the electric current, electrodes are mounted on the specimen surface 5 mm from the specimen edge. The electrodes are fabricated with a silver paste after polishing the surface of the specimen with abrasive paper to remove extra resin and so obtain a good electric contact between the silver paste and carbon fibers. The electrodes are then covered with epoxy resin for protection.

To investigate the antenna properties of CFRP specimens, the antenna return loss RL is measured using a return loss bridge (Kuranishi Instruments, BR-1), spectrum analyzer (Advantest, TR4131), and signal generator (Anritsu, MG3602A). The frequency of the sinusoidal wave from the signal generator is swept in the target frequency range, and the power spectrum is recorded with the spectrum analyzer at each frequency.

Next, wireless measurement tests are conducted. The CFRP specimen is used for the transmitting dipole antenna and an aluminum dipole antenna is used for the receiving antenna. The experimental setup is shown in Fig. 4. The wireless distance is set to 1 m. The signal generator sweeps the target frequency range, the radio waves transmitted from the CFRP antenna are received at the aluminum dipole antenna, and the power spectrum is observed using the spectrum analyzer.

Damage was introduced 80 mm from the outer edge of the specimen (element length 100 mm) by three-point bending. The damage includes delamination and fiber breakage in the surface layer. Although researchers have shown that electrical properties change with less severe damage such as applied strain, matrix cracking, and delamination [16],

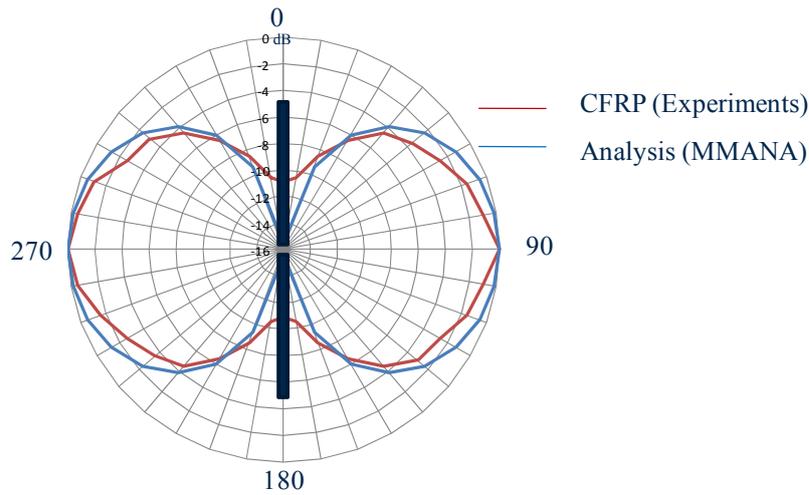


Fig. 5 Experimental and analytical two-dimensional radiation patterns of dipole antennas using the CFRP rectangular specimens. The analytical pattern was obtained using the antenna simulation software MMANA.

the pilot test in this research targets more severe damage that includes fiber breakage, which leads to enormous changes in electrical resistance.

3.3 Results and discussion

Fig. 5 shows the two-dimensional antenna radiation pattern using the CFRP rectangular specimen as half-wavelength dipole elements. The analytical value was obtained by antenna simulation using MMANA software, which is based on numerical electromagnetics code [14]. The experimental radiation pattern agrees well with the simulation results; hence, it is confirmed that the CFRP rectangular structure functions well as a dipole antenna.

Fig. 6 shows the frequency response of the antenna return loss using the CFRP rectangular specimen as a dipole antenna. The abscissa is the swept frequency and the ordinate is the return loss RL . Since the antenna radiates maximum radio energy at the resonant frequency, the return loss RL has a minimum at that frequency. It is seen from the experimental results that the intact CFRP specimen has a resonant frequency of 330 MHz while the analytical resonant frequency is about 390 MHz as shown in Fig. 3. The discrepancy may be due to an inductance effect around the electrodes, the CFRP itself, or electromagnetic effects around the antenna.

Fig. 6 also shows the frequency response of return loss RL of the damaged specimen. The resonant frequency increases to 570 MHz as the antenna element length shortens owing to interruption of the electric current path. The analytical resonant frequency obtained using the IE3D software is also shown in Fig. 6, and the trend of the increase in frequency due to damage agrees with the experiments. There is frequency discrepancy, as observed for the intact specimen. The return loss RL at the resonant frequency increases owing to damage because the antenna impedance and characteristic impedance of the line were not matched precisely in this test.

Fig. 7 shows the power spectrum of radio waves wirelessly received from the CFRP dipole antenna by sweeping frequency. The power spectrum peaks at 330 MHz and 570 MHz for the intact and damaged specimens respectively. These frequencies agree well

with the results of the return loss experiments though there is some radio noise observed in the wireless tests.

These results confirm that a damaged specimen can be modeled as a shortened antenna element and that its resonance frequency is increased by the damage. Thus the feasibility of wireless SHM using CFRP rectangular structures as antennas was demonstrated. Moreover, by measuring the frequency shift from the frequency for the intact specimen, the approximate location of the damage can be estimated. To validate this effectiveness more precisely, further experiments in which the location of damage is changed will be carried out in the future.

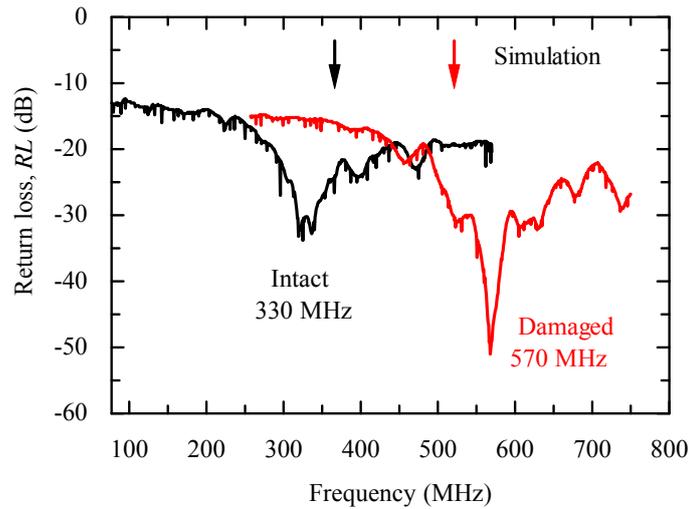


Fig. 6 Frequency response of the return loss RL of intact and damaged CFRP rectangular specimens as antennas. The arrows indicate the simulated resonant frequencies obtained using the IE3D simulator.

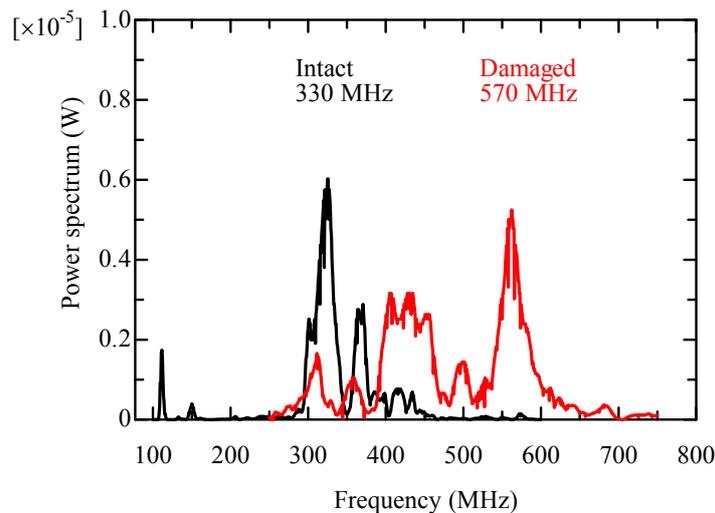


Fig. 7 Power spectrum of a wirelessly received signal from intact and damaged CFRP rectangular specimens as antennas.

4. CONCLUSIONS

The current work has shown that CFRP can be used as an antenna/sensor material. This technique enables the wireless SHM of whole CFRP structures functioning as an antenna, which reduces the number of sensors and amount of wireless equipment required. Comparing with the analytical antenna radiation pattern, we confirmed that CFRP rectangular laminates radiate radio energy well when used as half-wavelength dipole antennas. The feasibility of wireless SHM using the proposed multifunctional composites was investigated using unidirectional CFRP laminates. The experiments demonstrated that the damaged specimen can be modeled as shortened antenna elements and that its resonance frequency is increased by the damage. It was also suggested from antenna simulation results that the approximate location of the damage can be estimated by measuring the frequency shift from the frequency of the intact specimen.

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