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Electrical impedance spectroscopy for measuring the impedance response of carbon-fiber-reinforced polymer composite laminates

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Abstract

Techniques that monitor the change in the electrical properties of materials are promising for both non-destructive testing and structural health monitoring of carbon-fiber-reinforced polymers (CFRPs). However, achieving reliable monitoring using these techniques requires an in-depth understanding of the impedance response of these materials when subjected to an alternating electrical excitation, information that is only partially available in the literature. In this work, we investigate the electrical impedance spectroscopy response at various frequencies of laminates chosen to be representative of classical layups employed in composite structures. We clarify the relationship between the frequency of the electrical current, the conductivity of the surface ply and the probing depth for different CFRP configurations for more efficient electrical signal-based inspections. We also investigate the effect of the amplitude of the input signal.

Keywords: CFRP composites, Electrical impedance spectroscopy, Non-destructive testing, Electrical measurements.

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1. Introduction

Carbon-fiber-reinforced polymers (CFRPs) have been used efficiently for various structural applications, including primary structures for which safety is a major design requirement. The degradation phenomenology in CFRPs involves many different mechanisms of degradation [1] and often results in what is called barely visible impact damage. A typical example is the case of low-energy impact, for which a large delaminated area can exist without or with small dent on the skin of the structure [2, 3]. Contrary to metallic materials in which plasticity help containing damage evolution, CFRPs can experience catastrophic failure without prior notice [4]. It is thus important to develop a reliable structural health monitoring (SHM) technique that can both increase safety and reduce operational costs by optimizing inspection and repair [5]. So far, a number of SHM techniques have been developed, including dielectric spectroscopy [6], ultrasonic evaluation [7, 8, 9], vibration analysis [10], shearography [11], thermography [12], infrared thermography [13, 14], flash thermography [15], sampling phased array [16], dynamic modulus measurements [17], and acoustic emission monitoring [18, 19].

Due to inherent limitations of these techniques, there is a need to design a dedicated monitoring technique for large-scale composite structures that is capable of inspecting large composite parts during operation (online inspection). A viable approach is to use electrical inspection techniques, such as electrical resistance or electrical impedance methods because they are fast, low-cost real-time techniques [20, 21, 22]. Methods based on change in impedance (*i.e.*, electrical impedance spectroscopy (EIS) or electrical impedance tomography (EIT)) are suitable for off- and on-service monitoring, and can even be used in remote structural areas that are difficult to inspect. While direct current characterization (resistance measurement) has been extensively studied by a number of research groups [20, 21, 23], few groups have investigated methods of electrical impedance to characterize CFRP composites.

The EIS method measures the impedance response of the CFRP structure from the voltage-current data collected at the object boundary when a frequency sweep is applied [24, 25, 26]. A constant amplitude sinusoidal electrical signal is applied at different frequencies to study the frequency-dependent impedance response of the CFRP composites. EIS has been applied to investigate the mechanisms of electrochemical reactions, to measure the dielectric properties of materials [27], and to monitor the cure of plastics [28, 29]. It has also been used in non-invasive material characterizations of different composite materials [28, 30, 31, 32], including fibre-reinforced polymers [33, 34]. In addition, the impedance response of composite materials has been used as an SHM technique for CFRPs [30, 35, 36]. Preliminary results from EIS have characterized a few CFRP composites with some very specific layups in a limited range of frequency [36, 37]. Therefore, a systematic understanding of how CFRP composite laminates behave under the application of an alternating electrical signal is still needed.

CFRP composite materials are made of constituents with different electrical responses. Carbon fibers are electrically conductive but the matrix of the composite behaves as a highly resistive insulator [38]. The electrical conductivity of CFRP composite materials is in the range of $5.8 \times 10^4 - 1.1 \times 10^5 \text{ S/m}$ for carbon fibers [39, 40] and $10^{-13} - 10^{-10} \text{ S/m}$ for pure resin [41, 42]. The conductivity of a single ply varies with the volume fraction of the fibers and their geometrical distribution such that its conductivity is typically characterized as being anisotropic. The in-plane and out-of-plane transverse directions are much less conductive than the fiber direction although a residual transverse conductivity exists due to the random fiber-to-fiber contact within the ply [43]. At the meso-scale, additional capacitive layers are also induced by the rich resin interface in between plies of different orientations.

Here, we study the wide frequency range spectroscopic response of a variety of CFRP composite laminates, chosen as representative of typical stacking sequences of laminate used in CFRP composite structures. We consider surface plies that are highly conduc-

tive (*i.e.*, with fibers oriented about the probing direction), poorly conductive (*i.e.*, with fibers oriented perpendicularly to the probing direction) or moderately conductive. We investigate the role of frequency in the current penetration depth (designated as probing depth hereafter) for more efficient electrical-impedance-based inspections. We also perform mechanical tensile testing of selected samples to investigate the alternating signal sensitivity caused by the damage in the beam-type samples.

In section 2 of this paper, we describe the materials and methods, including sample fabrication, EIS, and mechanical testing instrumentation and procedures. In section 3, the results are discussed in terms of the electrical impedance behavior of CFRP composite laminates, the effect of voltage amplitude on the electrical impedance behavior, and the electrical equivalent circuit of the CFRP laminated composites.

2. Materials and methods

2.1. Sample fabrication

The sample were developed from carbon fiber prepregs made of a toughened epoxy resin and supplied by Hexcel Composites (HexPly M21/ 35%/ 268/ T700GC). The nominal fiber volume fraction was 56.9 %.

The experimental campaign was designed to investigate the impedance response of the CFRP laminated composites and to provide information about the probing capabilities of electrical-impedance-based techniques. One of our key objectives was to elucidate how deep the composite laminate can be probed. We previously reported [44] that the probing depth largely depends on the electrical conductivity of the surface-ply along the measurement direction. Because the composite ply has strong anisotropic electrical conductivity, the orientation of the surface-ply is expected to play a major role in how deeply the laminate can be probed. We list all sample configurations in Table 1.

The electrical conductivity was measured along the longitudinal direction of the

sample designated as 0°-direction. Three families of samples were fabricated, each of them with a primary orientation of the surface-ply. This orientation can be along 0° (fibers along the measurement direction), 45°- or 90°-direction (fibers orthogonal to the measurement direction). For each configuration, different sub-categories are tested to evaluate the effect of inner plies.

Specimen family	Stacking sequence	Tested specimens	Thickness (<i>mm</i>)
0°-orientation surface-ply	[0]	3	0.320 ± 0.007
	[0] ₂	3	0.580 ± 0.008
	[0] ₈	3	2.00 ± 0.04
	[0/45/90/ - 45] _s	3	2.00 ± 0.04
	[0/90] _{2s}	3	2.00 ± 0.04
45°-orientation surface-ply	[45]	3	0.320 ± 0.007
	[45] ₂	3	0.580 ± 0.008
	[45/ - 45] _{2s}	3	2.00 ± 0.04
	[45/0/45]	3	0.800 ± 0.013
	[45/90/45]	3	0.800 ± 0.013
90°-orientation surface-ply	[90]	3	0.320 ± 0.007
	[90] ₂	3	0.580 ± 0.008
	[90] ₈	3	2.00 ± 0.04
	[90/0/90]	3	0.800 ± 0.013

Table 1: Summary of the tested samples.

All of the samples were fabricated by compression molding of prepreg sheets. The following curing cycle was used: (1) full vacuum at 1 bar was applied to the whole stack to avoid air entrapment and the formation of voids; (2) 7 bar pressure was then applied through a hydraulic hot-press machine (Laboratory Press 15T, PEI France) at 180°C for 120 min; (3) the laminate was cooled to room temperature at 2°C/min. The obtained composite substrates were cut to the sample size as shown in (Fig. 1).

Figure 1: Schematic diagram showing the sample dimensions and the measurement method with the electrode configuration.

2.2. EIS instrumentation and procedures

All samples were equipped with silver paste electrodes housed on the specific electrode area. The electrode area ($5 \times 20 \text{ mm}^2$, Figure 1) was prepared by laser ablation to remove the surface resin as detailed in a previous work [45], and then cleaned with acetone. After masking the samples with vinyl tape, the silver paste (Electron Microscopy Sciences, USA) was applied to the unmasked locations for electrode fabrication. Wires were bonded to the silver paste by means of a conductive epoxy adhesive (ITW Chemtronics, USA). After curing of the adhesive, the mask was removed, the sample was cleaned, and the electrodes were covered with a protective layer of standard epoxy resin. Finally, glass-fiber epoxy taps, glued to each sample using Araldite 420 A/B adhesive (Huntsman, USA), were used to ensure electrical insulation between the sample and the frame of the universal testing machine.

The electrical impedance spectra were measured using an impedance analyser (Agilent-4294A Precision Impedance Analyzer) by applying an alternating voltage of 100 mV over a frequency range of ($40 \text{ Hz} - 2 \text{ MHz}$). The electrical impedance measurements were

carried out using the four-probe method (see Fig. 1). To observe the effect of the electrical voltage signal amplitude on the electrical impedance behavior, the impedance was measured for several values of electrical voltage (100, 300, 500 and 700 mV) and the results are discussed in the following section.

2.3. Mechanical Testing

Two types of tensile tests were conducted: monotonic and incremental cyclic tests. Both tests were displacement controlled with a loading speed of 0.5 mm/min using an Instron 5882 (Instron, USA) equipped with a 100-kN load cell. We selected samples representative of the 0° -orientation surface-ply family ($[0]_2$ samples), the 90° -orientation surface-ply family ($[90]_8$ samples), and a mixture of both (90° - 0° - 90° samples) (Table 2). During each cycle of the incremental loading scheme, the maximum load was increased incrementally by the value ΔP and the minimum load of the cycle was maintained at 50N. New cycles are added up to complete failure of the samples. The ΔP value for each type is detailed in Table 2. A dwell time of one minute was used for collecting the electrical impedance spectrum *in-situ* at the extrema of each cycle.

Specimen family	Stacking sequence	Loading step
0° -orientation surface-ply	$[0]_2$	$\Delta P = 1500$ N
90° -orientation surface-ply	$[90]_8$	$\Delta P = 250$ N
	$[90/0/90]$	$\Delta P = 750$ N

Table 2: Samples used in tensile test schemes.

3. Results and discussion

3.1. Electrical impedance behavior analysis

3.1.1. 0° -orientation surface-ply samples

Our first major observation was the very clear inductive behavior of the 0° -orientation surface-ply samples, which increased with increasing frequency. Figure 2(a) provides the

Bode plots (left y-axis: impedance, right y-axis: phase) for the unidirectional (UD) 0°-direction samples. Similarly to [35], we observed a predominant resistive behavior up to a frequency around 100 kHz . Note that the impedance and phase values differ from those reported in [35] because of differences in the electrical current injection patterns: in [35], the current was injected through the ends of the sample but we choose to inject the current from the skin because it seemed to be more representative of the structure of a real health monitoring configuration. When probing at higher frequencies, the impedance increased linearly with frequency, which is consistent with an inductive regime associated with a network of carbon fibers. Indeed, these fibers behave as a network of parallel conductors, which develop both self and mutual inductance (Fig. 2(c) and (d)). We recall that the self-inductance of two parallel straight wires of length l , radius ρ , and distance a apart can be approximated as [46]:

$$L \approx \frac{\mu_r \mu_0 l}{2\pi} \left[\log \frac{2l}{\sqrt{r_g a}} - 1 \right] \quad (1)$$

where μ_0 is the vacuum permeability ($4 \cdot 10^{-7} \text{ H/m}$), μ_r is the relative magnetic permeability of the conductor, and r_g is the geometric mean distance of the section of the wire (0.7788ρ). At a particular frequency (f), the inductance will produce the inductive reactance ($X_L = 2\pi f L$), which will contribute to the development of the potential across the carbon fibers.

Figure 2: The bode plot of the electrical impedance magnitude and phase angle response with log frequency of (a) single-ply (SP) 0° -orientation, double-ply (DP) 0° -orientation surface-ply and 8-ply unidirectional (UD) 0° -orientation surface-ply, where the inset shows the linear impedance behavior with respect to frequency, and (b) the electrical impedance response for all samples with 0° -orientation surface-ply including the quasi-isotropic (QI) $[0/45/90/-45]_s$ and the cross-ply (CP) $[0/90]_{2s}$. The inset shows the linear impedance behavior. (c) AC conduction through a single carbon fiber (straight conductor) and the associated magnetic flux, and (d) schematic of the four-electrode impedance measurement in a 0° -orientation surface-ply of CFRP laminates.

Our second major observation was that when the surface-ply was oriented along the direction of the electrical measurement, the probing depth is very small. Indeed, we superimposed the Bode plots obtained for the cross-ply (CP) and the quasi-isotropic (QI) laminates onto UD plots to find that these laminates behave similarly, testifying that the overall impedance response is only sensitive to the orientation of the first ply (Figure 2(a) and (b)). We found that the second ply from the surface (at 90° , 45° , or 0°

directions) did not influence the overall response because most of the current actually flows within the surface-ply. The low impedance of the surface-ply compared to the high impedance of the resin-rich layer (average thickness around $30\mu m$) isolates each ply (see Figure 3 on the cross-sectional image of an 8-ply CFRP-laminated composite specimen).

Figure 3: Cross-sectional image of (a) the UD laminate, and (b) the inset image of the rich resin layer showing the average thickness value.

Third, we tracked the changes in the spectroscopic response with loading to determine whether spectrum observations could be a robust indicator of fiber direction for health monitoring. As mentioned in section 2.3, samples were loaded with a cyclic loading/unloading scheme, while the maximum loading was increased incrementally by 1500 N between subsequent cycles. The results for 0° -orientation surface-ply DP samples are reported (Figure 4(a) and (b)). We observed no major difference between spectra in the loaded and unloaded state up to the 5th cycle. Perturbations of the spectra appear only very late close to final failure, and mainly for low frequencies (below 0.5MHz). As observed in Fig. 4(c), only the resistive part of the behavior was truly affected, whereby loading resulted in a progressive shift of the Z curves toward lower values. The phase curve (Fig. 4(d)) suffers stronger modifications toward the end of the loading, but again very close to final failure.

Figure 4: The electrical spectroscopy of the $[0]_2$ samples for each loading cycle at given frequency values for: (a) the impedance magnitude, (b) the phase angle, (c) the impedance magnitude response over the frequency range, and (d) the phase-angle response over the frequency range.

3.1.2. 45° -orientation surface-ply samples

We investigated the 45° -orientation surface-ply samples by studying the response of single-ply 45° , double-ply 45° , and $[45/-45]_{2s}$ laminates (Fig. 5). In Figure 5(a), the blue- and gray-shaded areas indicate the standard deviation of the tested specimens for each type of laminate.

The resistive behavior of 45° -direction samples was dominant up to 100 kHz although the impedance was much higher. Above 100 kHz , a clear capacitive behavior was observed. Both of these observations can be attributed to the microstructure of the 45° -direction samples. In these surface-ply laminates, most of the fibers connect to only

one electrode, so the conduction path has to go through the interfiber resin (Fig. 5(c)), which considerably increases the effective impedance, behaving as a capacitor at high frequencies (Fig. 5(e)).

Likewise, the $\pm 45^\circ$ angle-ply laminate shows a resistive behavior up to 100 kHz and a capacitive behavior beyond this frequency value. Similar to the 45° laminates, no carbon fibers directly connect to the electrodes. Because direct conduction of the electrical signal through the surface-ply is difficult, electrical conduction is observed through the capacitance produced between carbon fibers and the second ply (-45°) (Fig. 5(d) and (f)). Thus, we can then expect that the relatively high impedance of the surface-ply promotes current penetration through the resin-rich interface between plies. Current conduction can then take place within the fibers of the second ply. As a result, the impedance of the $[45/-45]_{2s}$ laminates is lower than that with pure -45° -orientation, but with similar capacitive features.

Our main conclusion here is that when the impedance of the surface-ply along the measurement direction is high enough, the effective response is dependent on at least the second ply, making it possible to probe the material deeper. To validate this understanding, we fabricated two other configurations by changing the orientation of the second ply to either 0° - or 90° -direction ($[45^\circ/0^\circ/45^\circ]$ and $[45^\circ/90^\circ/45^\circ]$ stacking sequences, see Table 1). In Figure 6(a), the observed inductive spectrum similar to that observed in Fig. 2 clearly indicates that the response of the $[45^\circ/0^\circ/45^\circ]$ was mainly guided by the inner 0° -direction ply (Fig. 6(c)). In Figure 6(b), we observed a capacitive effect but with a relatively low impedance that is unexpected for such samples. This can be explained by the 90° -direction fibers, which short circuit the gap between the current carrying fibers of the surface angle ply (Fig. 6(d)). In both cases, inner plies were efficiently probed due to the high impedance of the surface layer along the measurement direction.

Figure 5: The Bode plots of the electrical impedance magnitude and phase-angle response with log frequency of (a) single (SP) and double (DP) 45° -orientation laminates, where the shaded area is the standard deviation of the tested samples; (b) $\pm 45^\circ$ 8-ply laminates. (c) & (d) Schematics of the four-electrode impedance measurement for 45° -orientation and $\pm 45^\circ$ 8-ply laminates, respectively. (e) & (f) Schematics of the capacitance produced between the fibers and between the inter-layer fibers, respectively.

Figure 6: The Bode plots of the electrical impedance magnitude and phase-angle response with log frequency of (a) $[45^\circ/0^\circ/45^\circ]$ laminate and (b) $[45^\circ/90^\circ/45^\circ]$ laminate, where the shaded area is the standard deviation of the tested samples. (c) & (d) Schematics of the electrical current flow in 45-0-45 and 45-90-45 samples, respectively.

3.1.3. 90° -orientation surface-ply samples

The bode plots of the 90° -direction laminates (Fig. 7(a) and (b)) show that the capacitive behavior of such laminates is dominant from the beginning of the frequency range. When an alternating voltage is applied, direct conduction through single 90° -direction laminates (Fig. 7(c)) is difficult because the carbon fibers are in parallel. Fiber-fiber contact rarely provides a continuous path from the positive voltage electrode to the negative voltage electrode, and thus, the current fails to take a continuous current path of conduction. Thus, in the 90° -direction laminate, capacitance between the parallel carbon fibers serves as the major paths of conduction for alternating current. The reactance

produced by the intra-layer capacitance (Fig. 7(e)) in the 90°-direction laminate is comparatively more than in the single layer because the current has to pass through a number of resin layers, as shown in the schematic (Fig. 7(c)), producing very high overall capacitive reactance.

Figure 7: The Bode plots of the electrical impedance magnitude and phase-angle response with log frequency of (a) single and double 90°-orientation laminates and (b) 90°-orientation 8-ply laminates. (c) Schematic of the four-electrode impedance measurement of these laminates and its conduction path, (d) frequency response of impedance magnitude and phase angle of [90°/0°/90°] laminates, and (e) intra-layer capacitance and inter-layer capacitance in double 90°-orientation laminates.

In double 90°-orientation laminates, voltage application affects the impedance response similarly to that in the 90°-orientation single ply: the orientation of fibers in the

surface layer was similar in both single- and double-ply laminates. However in the 90° -orientation double ply, inter-layer capacitances between the fibers of the surface layer and the fibers of the under layer change the impedance behavior. Thus, the current passes through two conductive paths: the top intra-layer and the bottom layer as shown in (Fig. 7(e)). Thus, the impedance of the 90° -orientation double ply was lower than in the 90° -orientation single ply.

To confirm this concept of current penetration, a 0° -orientation ply was introduced in the middle between the upper and lower 90° plies of the double-ply laminate to produce a $[90^\circ/0^\circ/90^\circ]$ laminate. The electrical impedance was similar to the $[45^\circ/0^\circ/45^\circ]$ laminate, dominated by the 0° -orientation ply.

Figure 8: The electrical spectroscopy of the 90° -orientation 8-ply for each loading cycle at a given frequency for (a) the impedance, (b) the phase angle, and (c) the phase-angle response over the same frequency range.

Next, we wanted to observe the electrical impedance behavior of 90° -orientation surface-ply laminates under mechanical loading. The $[90]_8$ samples were tested with the monotonic test scheme and the electrical impedance response was collected. (Figure 8(a) and (b)) reveals the impedance magnitude and phase-angle responses to the mechanical test, where the abscissa is the number of loading cycles and the ordinates are the impedance magnitude and the phase angle. Each curve was evaluated at a given frequency range starting from 40Hz to 2MHz by steps of 0.25MHz. We observed that increasing the frequency caused a major drop in the impedance magnitude and the phase angle. We expected this result because we know that the interfiber capacitive resin layer

plays a major role in the conduction process. Note that the spectroscopic spectra were very stable with little modification up to failure, which we understand as strengthening of the structure from the very brittle failure process of pure 90° -orientation samples, in which the first initiation of damage results in the final failure of the sample.

We also tested cross-ply ($[90^\circ/0^\circ/90^\circ]$) laminates with the incremental cyclic test scheme. Figure 9(a) and (b) reveals the electrical impedance magnitude and phase-angle responses to the mechanical test, where the abscissa is the number of loading cycles and the ordinates are the impedance magnitude and phase angle. Each curve was evaluated at a given frequency range starting from 40Hz to 2MHz by steps of 0.25MHz. The vertical green dashed-line represents the development of transverse cracks that occurred during the early loading cycles while the vertical blue dashed-line represents the development of damage in fibers. We observed a mixture of electrical impedance behavior between the 90° -orientation and 0° -orientation behaviors for such cross-ply laminates with increasing frequency. The impedance magnitude behaved similarly to that of the 90° -orientation laminates up to a threshold frequency value of around 1MHz and their phase angles were similar around 0.5MHz, where both values drop with increasing frequency. Beyond their respective threshold values, the behavior becomes similar to the 0° -orientation laminates, where both the impedance magnitude and phase angle increase with increasing frequency. Thus, we can say that the frequency did not contribute to the penetration of the electrical current although it can facilitate the penetration if there is an easy path below the surface-ply for the electrical signal to follow. Damage appeared to have little effect on the variation in impedance magnitude while a clear decrease in the phase angle variation was observed (Fig. 9(c)). During early loading cycles, before the development of damage, we see an absence of variation to the electrical impedance response between loaded and unloaded conditions (Fig. 9(d)).

Figure 9: The electrical spectroscopy of the $[90^\circ/0^\circ/90^\circ]$ laminate for each loading cycle at given frequency values for (a) the impedance magnitude and (b) the phase angle. (c) The impedance response, and (d) the electrical impedance response over the same frequency range before the development of damage.

3.2. The effect of electrical voltage amplitude on electrical measurements

Based on the results in the previous subsection, we decided to study the effect of the electrical voltage amplitude on the electrical measurements. We applied different electrical voltage amplitudes (100, 300, 500, and 700 mV) to the same samples and collected their responses. We observed no significant effect of the electrical voltage amplitude on the electrical impedance of the laminates with the 0° -orientation surface-ply (Fig. 10).

Figure 10: The frequency response of electrical impedance and phase angle of 0° -orientation surface-ply laminates with increasing amplitude of the electrical voltage values; the shaded area is the standard deviation of the tested samples.

We observed different electrical impedances with 45° -orientation surface-ply and the $\pm 45^\circ$ 8-ply laminates (Fig. 11(a) and (b)) compared to 0° -orientation surface-ply laminates. As the electrical voltage increased, the impedance dropped slightly (Fig. 11(b)). The 45° -orientation surface-ply laminates had the same behavior but different phase-angle response with increasing voltage at high frequency because the underlying plies have the same orientation as the surface-ply (Fig. 11(a)).

Figure 11: The frequency response of electrical impedance and phase angle with increasing amplitude of the electrical voltage of (a) single and double 45°-orientation ply laminates, (b) $\pm 45^\circ$ 8-ply laminates, (c) $[45^\circ/0^\circ/45^\circ]$ laminate, and (d) $[45^\circ/90^\circ/45^\circ]$ laminates.

Similar to the response of 0°-orientation surface-ply laminates, $[45^\circ/0^\circ/45^\circ]$ laminates demonstrate a slight decrease in the amplitude of electrical impedance due to the 45°-orientation ply (Fig. 11(c)). In the $[45^\circ/90^\circ/45^\circ]$ laminates (Fig. 11(d)), the 90°-orientation ply induced a greater drop in the impedance amplitude compared to what we observed in the 0°-orientation ply of the $[45^\circ/0^\circ/45^\circ]$ laminates. This result confirms the effect of the sub-surface ply on current penetration and impedance behavior.

In the 90°-orientation surface-ply laminates, however, a slightly larger drop in the

impedance amplitude was observed with increasing voltage input signal because the scale of the impedance of single- and double-ply 90°-orientation laminates is in the $k\Omega$ range (Fig. 12(a)). The 90°-orientation 8-ply laminate exhibited a slight drop in the impedance amplitude (Fig. 12(b)), while the [90°/0°/90°] laminates behaved similarly to [45°/0°/45°] because they share the 0°-orientation ply in their sub-surfaces (Fig. 12(c)). We observed this behavior in the off-axis (45°- and 90°-orientation) surface-ply laminates, but not in on-axis laminates (along fibers direction) or in laminates where the 0°-orientation fibers were close to the surface.

Figure 12: The frequency response of electrical impedance and phase angle with increasing amplitude of the electrical voltage values of (a) single- and double-ply 90°-orientation laminates, (b) 90°-orientation 8-ply laminate, and (c) [90°/0°/90°] laminate.

4. Conclusion

EIS studies conducted on CFRP composites demonstrated the electrical impedance behavior of CFRP laminates with various stacking sequences. Results show that the depth probing capability of this technique is highly dependent on the conductivity of the surface along the measurement direction. All CFRP laminates with a 0° -orientation ply at the surface had the same impedance behavior because all of the carbon fibers come into direct contact with the electrodes, providing highly conductive electrical paths for the current flow. Hence the current conducts best through the surface layer, avoiding lower layers. Meanwhile, laminates with 45° -orientation surface-ply or 90° -orientation surface-ply laminates had current that penetrated deeper into the composite. Although we observed a slight difference in the impedance of the CFRP laminated samples with different applied amplitude input voltage, a detailed study is required to explore this phenomena. We expect the results from this work to contribute to the design of measurement systems using electrical tomography to monitor damage of laminated composite structures.

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