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Biphasic DC measurement approach for enhanced measurement stability and multi-channel sampling of self-sensing multi-functional structural materials doped with carbon-based additives

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Abstract

Investigation of multi-functional carbon-based self-sensing structural materials for structural health monitoring applications is a topic of growing interest. These materials are self-sensing in the sense that they can provide measurable electrical outputs corresponding to physical changes such as strain or induced damage. Nevertheless, the development of an appropriate measurement technique for such materials is yet to be achieved, as many results in the literature suggest that these materials exhibit a drift in their output when measured with direct current (DC) methods. In most of the cases, the electrical output is a resistance and the reported drift is an increase in resistance from the time the measurement starts due to material polarization. Alternating current methods seem more appropriate at eliminating the time drift. However, published results show they are not immune to drift. Moreover, the use of multiple impedance measurement devices (LCR meters) does not allow for the simultaneous multi-channel sampling of multi-sectioned self-sensing materials due to signal crosstalk. The capability to simultaneously monitor multiple sections of self-sensing structural materials is needed to deploy these multi-functional materials for structural health monitoring. Here, a biphasic DC measurement approach with a periodic measure/discharge cycle in the form of a square wave sensing current is used to provide consistent, stable resistance measurements for self-sensing structural materials. DC measurements are made during the measurement region of the square wave while material depolarization is obtained during the discharge region of the periodic signal. The proposed technique is experimentally shown to remove the signal drift in a carbon-based self-sensing cementitious material while providing simultaneous multi-channel measurements of a multi-sectioned self-sensing material. The application of the proposed electrical measurement technique appears promising for real-time utilization of self-sensing materials in structural health monitoring.

Keywords: self-sensing structural materials, carbon-based sensors, structural health monitoring, smart structures, smart materials, measurement techniques

(Some figures may appear in colour only in the online journal)

1. Introduction

Self-sensing materials are defined by their ability to monitor their own conditions [1]. Popular applications supplement structural materials for self-sensing actuation [2] and control of complex structures [3, 4]. Self-sensing structural materials have received considerable research interest for their potential use in structural health monitoring (SHM). Of particular interest to this work is the introduction of carbon-based fillers into traditional structural materials to develop fully integrated, self-sensing materials. These materials may be used for strain-sensing [5] or crack/delamination damage detection [6].

Numerous matrices, functional fillers and applications of self-sensing structural materials utilizing carbon-based additives have been proposed in recent years, as extensively documented in the literature [1, 7–9]. In particular, various carbon-based self-sensing structural materials have demonstrated strain sensing [5, 6] and damage detecting capabilities through the use of impedance/resistance measurements [6, 10]. On the filler-matrix interaction level, numerous researchers have developed and deployed piezoresistive cement-based materials for strain sensing through the doping of the cement matrix with carbon fibers [11], carbon black [12] and multiwall carbon nanotubes (MWCNTs) [13]. Additionally, carbon-based fillers have been used to significantly improve the materials properties of cementitious materials [14].

The body of research presented here have used direct current (DC) for the extraction of various electrical parameters (e.g. voltage, resistance and conductivity). DC measurements were taken using either a two-probe or four-probe configuration. The two-probe method uses a single probe to source current and measure voltage, while the second probe sinks current and provides a voltage reference. In comparison, the four-probe method uses separate pairs of current-carrying and voltage-sensing probes. The four-probe method can provide more accurate results as it bypasses the measurement cables' resistance and the contact resistance at the signal/sample interface [15]. However, the two-probe method provides a simpler configuration as it requires only two signal/sample interfaces. Typically the electrical resistance caused by the electrochemical reaction between metal contacts and carbon-based materials in often non-trivial [16]. However, the value of the contact resistance may be negligible in the case of highly resistive samples or may drop out if only the relative change in resistance is needed assuming that the contact resistance remains constant.

While DC current has shown useful for laboratory characterization of self-sensing structural materials, it tends to induce an inherent time-based drift in a multi-functional material's output. The drift tends to represent itself as an increase in the resistance starting from the time the resistance measurement starts. This characteristic shape can be seen in the authors' work [17–20] and is presumed to be a factor in the drift present in the works of other authors [11, 13, 21–24]. This drift is often attributed to material polarization [23, 25], changes in materials dielectric constant [21, 26] or direct piezoelectric effect [27]. Many researchers have attempted to mitigate the materials drift through comparing a sensing material with a control sample [28] or delaying measurements until the drift levels out (see [19, 27, 29] for instance). This technique may be acceptable for dynamic measurements, but is less suitable for static measurements.

Some AC methods have been applied for measurement and material characterization of self-sensing structural materials [21, 28, 30]. AC measurement techniques seem more appropriate at eliminating the time drift, owing to a continuous electrical charging and discharging of the sample. However, electrical characteristics extracted from AC measurement techniques demonstrate that they are not immune to drift [21, 24, 31]. Also, multiple impedance measurement devices, commonly referred to as LCR meters, do not typically allow a simultaneous acquisition of data from multi-sectioned self-sensing materials due to interactions between the different LCRs' sensing currents. For example, using multiple LCRs for simultaneously monitoring of multiple adjacent sections of a carbon-doped concrete beam will cause a high level of signal crosstalk. The ability to simultaneously monitor multiple adjacent sections is critical for the deployment of multi-functional materials in SHM systems as it enables real-time damage detection and localization. Furthermore, traditional AC parameters such as reactance, impedance and phase angle require the use of expensive electronic equipment [30] and may require the use of fast sampling digitizers and processors to obtain and calculate measurement values [32], generally increasing the costs associated with the deployment of a self-sensing system. Due to the restraints of traditional DC (material polarization) and AC (simultaneous multi-channel measurements) measurement techniques, the introduction of a measurement technique specifically formulated for monitoring of multi-sectioned carbon-based self-sensing materials is highly needed.

In this paper, the authors present an electrical characteristics measurement approach that highly reduces the effect of sensor drift found in various self-sensing structural materials, while allowing independent sections of a self-sensing material to be monitored simultaneously. The proposed measurement method is developed around the theory that the drift present in carbon-based self-sensing materials is an intrinsic material property that develops from the polarization of the material as a function of the time a sensing current is applied to the material. This material polarization is considered to be fully dependent on the direction of sensing current flow as the self-sensing material is itself not intrinsically polarized. Hence, the action of taking measurements is itself the cause of material polarization and, therefore, the cause of the materials resistance drift. The effect of the polarization can then be reversed by reversing the direction of the sensing current flow.

Here, the proposed biphasic biased DC measurement approach provides consistent and stable long-term results by continuously charging and discharging the self-sensing material. Material sensing is provided by a periodic measure/discharge square wave, where DC measurements are made during the measurement region of the square wave. Material depolarization is obtained through reversing the applied current during the discharge region of the periodic signal. This DC measurement approach allows for the simultaneous, multi-channel resistance-based monitoring of a self-sensing structural material through obtaining multiple voltage measurements from a multi-sectioned carbon-based multi-functional material.

The contributions in this paper are threefold: (1) a biphasic DC measurement approach for self-sensing materials used in SHM applications is introduced and its ability to remove drift in carbon-based self-sensing materials is shown; (2) the biphasic DC measurement approach is shown to be well suited for the characterization of a strain-sensing structural material, consisting of MWCNTs suspended in a cement paste matrix, over a range of static strains; and (3) the novel measurement technique is validated for applications involving simultaneous, multi-channel measurements of a sectioned self-sensing structural material. Comparison of strain sensitivity based on various electrical measurement techniques is difficult as these effects are material-based and each carbon-based material will react differently to various measurements techniques. Therefore, a comprehensive comparison between various measurement techniques is beyond the scope of this introductory work.

This paper is organized as follows. The self-sensing structural material used throughout this work is introduced in section 2. The biphasic measurement approach is introduced in section 3. Results and corresponding discussion from the experimental validation are presented in 4 and section 5 concludes this work.

2. Background

The fabrication process and sensing principles of an MWCNT-based self-sensing cementitious material are described in details in [18]. Briefly, these carbon nanotube cement-based composites are made by doping traditional cementitious mixtures with carbon nanotubes. Such doping provides the cement-based composite with a piezoresistive strain sensing capability. In the presented experiments, 1% MWCNT (Arkema C100) with respect to the mass of cement was added to water along with a surfactant (Lignosulfonic acid sodium salt) and mixed using a sonicator tip after a preliminary mechanical mixing. Two specimens were cast: the first into a 51 × 51 × 51 mm mold along with five stainless steel mesh electrodes (4 × 4 Mesh, 1.2 mm wire) as shown in figure 1(a) and the second into a 40 × 40 × 160 mm mold along with eight stainless steel mesh electrodes (4 × 4 Mesh, 1.2 mm wire) as shown in figure 1(b). Each specimen was cured for 28 days before testing.

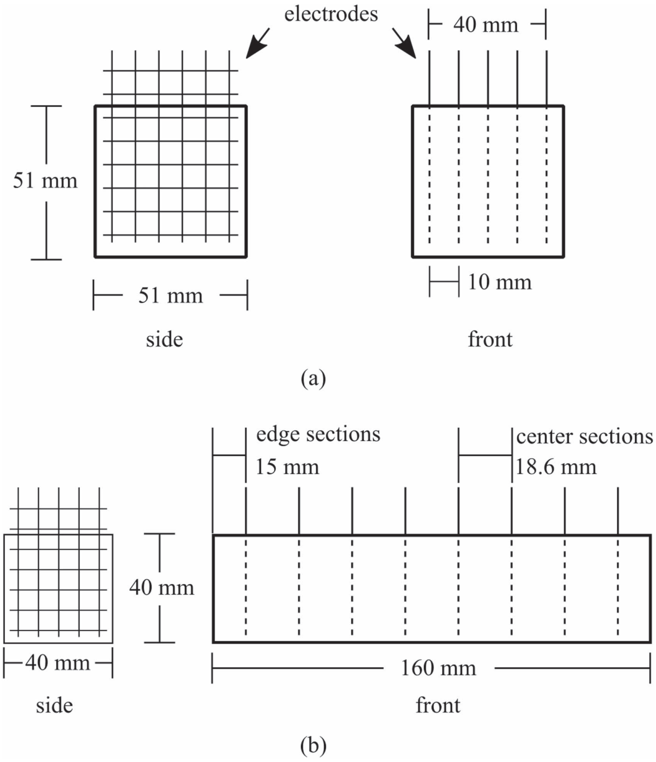

Figure 1. Self-sensing structural material consisting of MWCNTs suspended in a cement matrix with stainless steel mesh used for connectors: (a) 51 × 51 × 51 mm cube sample for validating the proposed biphasic measurement approach; (b) 40 × 40 × 160 mm unreinforced beam for demonstrating simultaneous, multi-channel resistance measurements.

Various equivalent electromechanical models for strain-sensing cement-based materials doped MWCNTs have been introduced [20, 33]. Models consisting of lumped passive circuits of various arrangements have been deployed with mechanical deformation being directly related to varying circuit parameters, resulting in strain-dependent electrical models for the self-sensing material. These models typically conclude that only resistance is influenced by the mechanical deformation [20, 33, 34]. Therefore, we reduce the resistance–strain relationship to

$$\frac{\Delta R}{R} = -\lambda\varepsilon, \tag{1}$$

where λ is the gauge factor, R is the specimen's unstrained nominal resistance and ΔR is the incremental variation in electrical resistance caused by the axial strain (ε). The biphasic measurement approach presented here, while proposed for the monitoring of piezoresistive self-sensing structural materials, is theoretically capable of monitoring the change in capacitance, ΔC, caused by deformation. However, based on previously documented work (see [33] for example) we conclude that the piezoresistive effect is many orders of magnitude greater than the piezocapacitve effect for the carbon-based self-sensing materials of interest. Therefore, any ΔC caused by material deformation is considered inconsequential and is neglected for the purpose of this work.

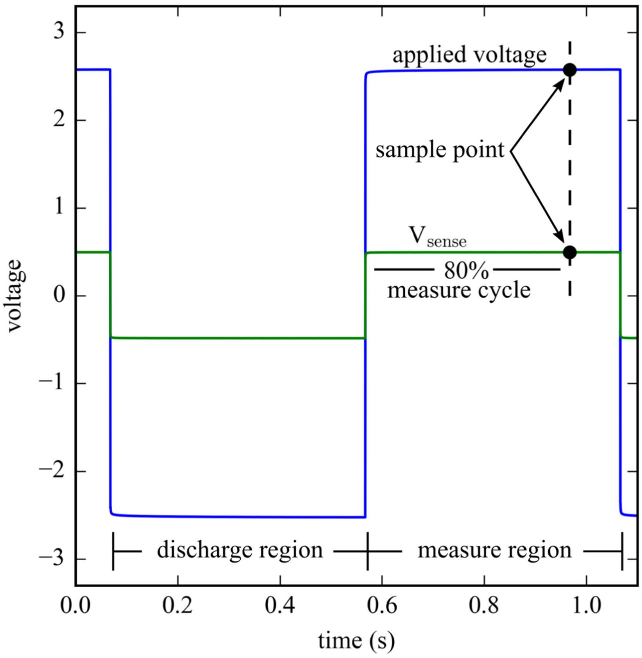

Figure 2. Electrical signals of a 1 Hz square wave: sensing current with 50% duty cycle showing the discharge and measure regions, as well as the sample points for the applied and sense voltages.

3. Biphasic measurement approach

The proposed biphasic electrical measurement approach works by sourcing a periodic measure/discharge signal in the form of a square wave from a signal generator. The action of discharging the self-sensing material between measurement cycles provides a constant and repeatable measurement over time. DC voltage measurements are made during the signal's measure region while material depolarization is obtained during the discharge region of the periodic signal. Resistance values for the self-sensing structural material are obtained by dividing the measured voltage (V_{sense}) by the current flowing through the specimen [15]. Current ($i_{\text{calculated}}$) is calculated by monitoring the voltage drop across a known resistor, arranged in series with the specimen that is being monitored. The current transiting through the known resistor and therefore through the cement paste sensor, can be calculated as:

$$i_{\text{calculated}} = \frac{V_{\text{drop}}}{R_{\text{in-line}}}, \tag{2}$$

where $R_{\text{in-line}}$ is the resistance value of the in-line resistor and V_{drop} is the voltage drop across the resistor. Figure 2 diagrams the applied voltage as well as the sensing voltage signal for the cube cement-paste sensor introduced in figure 1(a). Here, a 1 Hz square wave ranging from −2.5 to 2.5 V with a duty cycle of 50% was used as the sensing current. The experimental configuration is presented in figures 3(a), (b). Discrete voltage samples are taken during each measure region of the square wave at a constant time interval from the start of the measure region. For this work, samples are taken at 80% of the measurement cycle as denoted in figure 2. Dividing the measured voltage by the simultaneously measured current ($i_{\text{calculated}}$) results in a resistance value,

$$R = \frac{V_{\text{sense}}}{i_{\text{calculated}}}, \tag{3}$$

where the sampling rate of R in samples per second (S/s) is determined by the frequency of the sensing current, measured in Hz. Therefore, the sampling frequency of the biphasic DC measurement approach coincides with the frequency of the applied sensing current, with one sample per complete discharge-measure cycle. The resistance results can be related directly to the change in strain with equation (1) for a strain-sensing material [5] or a damage condition for a damage-detecting material [6]. The biphasic DC measurement approach can be implemented in either a two-probe or four-probe method, however, only a four-probe method is used in this work.

3.1. Methodology for experimental validation

Experimental validation of the biphasic measurement approach using four-probe resistance measurements is conducted using a static test configuration as shown in figures 3(a), (b). The nanocomposite cement-paste cube (figure 1(a)) is placed in a frame consisting of an F-clamp. Steel blocks are used to evenly distribute the applied load onto the test specimen. A piece of cardboard is used to insulate the test specimen from the steel blocks. A steel ball is used as a pivot to remove any eccentricity in the loading. The same approach is used for dynamic testing, however, the F-clamp frame is replaced with a servo-controlled pneumatic universal testing machine (model IPC Global UTM14P).

A PXIe-4302 24 bit analog input module is used for sampling V_{sense} and V_{drop} in a differential voltage configuration. Voltage measurements are hardware-timed and taken at 5000 S/s. Voltage samples used for calculating the resistance are taken as the voltage sample closest in time to the 80% mark of the measurement cycle. No filtering is applied to the raw voltage measurements. A signal generator (Philips PM5132) with an output impedance of 600 Ω is used to provide the sensing current for both the biphasic measurement approach and DC measurement. A wire round resistor placed in series with the specimen to be tested is used to calculate current. All signal cables use tinned-copper screw-type connectors and are constructed to be as reasonably short as possible and consist of RG174 coaxial cable with the shield connected to earth ground. Continuous measurements are taken for strain, load and voltage. Two strain gauges (KYOWA KC-120-120-A1-11M2R) were adhered onto opposite sides of the specimens and strain is taken as the average of the two measurements. A 2000 kg load cell (LAUMAS CL 2000) is installed to monitor the compressive force applied in the systems. Measurements are obtained using a custom LabVIEW script interfaced over a PXIe-1071 chassis from National Instruments with a PXIe-4330 24-Bit bridge input module used for obtaining strain gauges and load cell measurements. Signal ground is referenced to a mesh

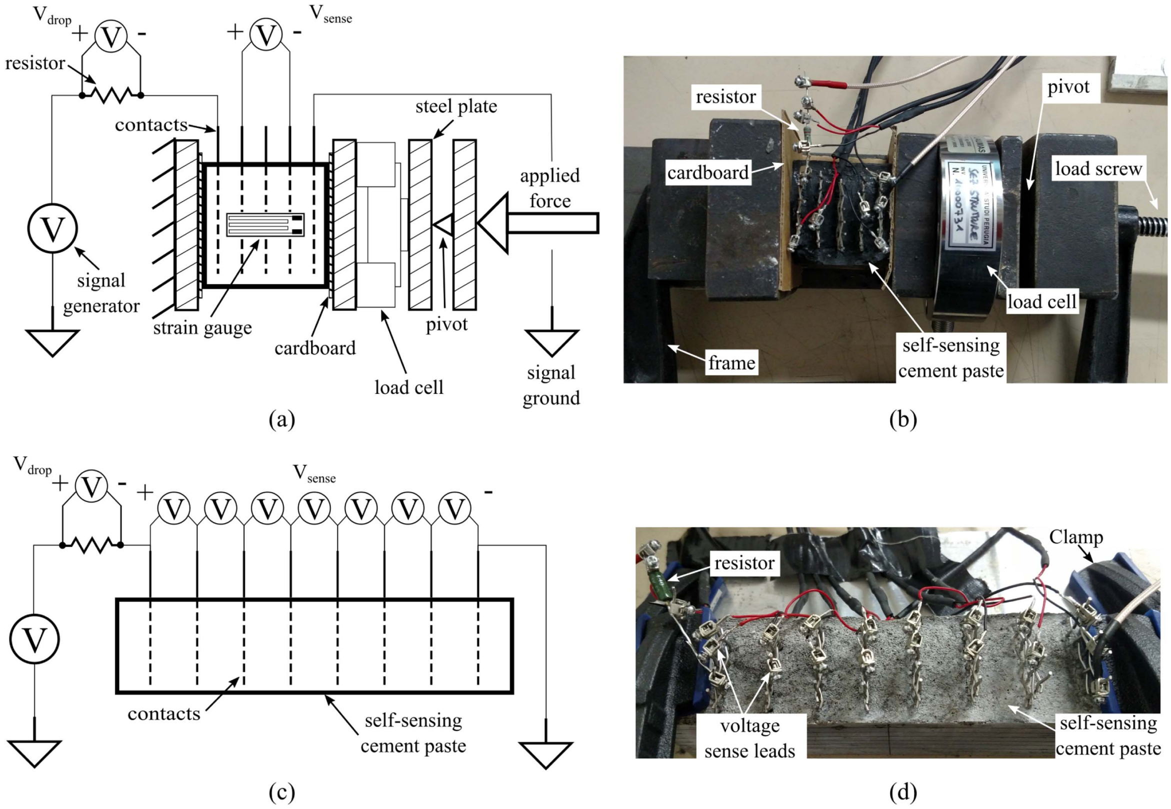

Figure 3. Experimental configurations: (a) electro-mechanical diagram of the cube test configuration with key components labeled; (b) picture of the cube test configuration; (c) electro-mechanical diagram of the beam test configuration; (d) picture of the beam test configuration.

contact on the test specimen as diagrammed in figures 3(a) and (c).

First, results obtained from the proposed biphasic DC measurement approach using a variety of sensing current frequencies with a 50% duty cycle are compared to those obtained from a DC resistance measurement in the time domain for a test length of 100 s. Sensing current frequencies of 1, 2, 5, 10, 20, 50, 100, 200 and 400 Hz are investigated. In all cases, a square wave with voltages of -2.5 and 2.5 V is applied to the specimen under a constant loading of 1.0 kN. Before testing, the specimen is completely discharged by connecting all five electrodes together for 5 min to remove any residual charge left in the specimen. During testing, the signal current is introduced at 1 s and the sensor response in resistance is measured for 100 s. Second, the effects of sensor discharge is investigated by alternating the square wave's duty cycle, whereby duty cycles of 50%, 60%, 70%, 80% and 90% are investigated. For the duty cycle tests, the voltage sample is taken at the time corresponding to 80% of the 50% duty cycle for all tests to enable comparison of the voltage samples between varying tests. Third, the effects of a square wave ranging from 0 to 2.5 V on the sensor drift are investigated to demonstrate the effect of non-reversing current flow on sensor discharge. Fourth, the ability of the cement paste doped with MWCNT to function as a strain-sensing structural material using the proposed biphasic measurement approach is verified using a sensing current frequency of 1 Hz. The specimens' linear range is then found and used to investigate the sensitivity of the sensor for the sensing current frequencies of 2, 5, 10, 20, 50, 100, 200 and 400 Hz. Fifth, the ability of the biphasic DC measurement approach to capture a sensor's dynamic strain response is verified over mechanical loading range of 1–6 Hz. Dynamic testing is performed on a universal testing machine with a sinusoidal compression load varying between 0.6 and 1.6 kN.

The capability of the biphasic measurement approach in simultaneously monitoring multiple sections of a self-sensing structural material is validated using the beam sample presented in figure 1(b). The test setup is presented in figures 3(c), (d). The same data acquisition hardware is used as before. The specimen is lightly clamped to the test bench to prevent movement. Sensing voltage is sampled as the differential voltage between a set of adjacent contacts, denoted as V_{sense} in figure 3(c), allowing the resistance of individual sections to be monitored. Current is assumed to flow fully through all sections of the beam. Therefore, the resistance of individual sections can be calculated with the use of a simple resistor-based model. No strain sensing tests are performed on this sample. Lastly, a brief investigation of the noise present in the measured resistance signal is conducted.

4. Results

This section presents results for the biphasic measurement approach's ability to reduce sensor drift, monitor strain-sensitive self-sensing structural materials and perform simultaneous

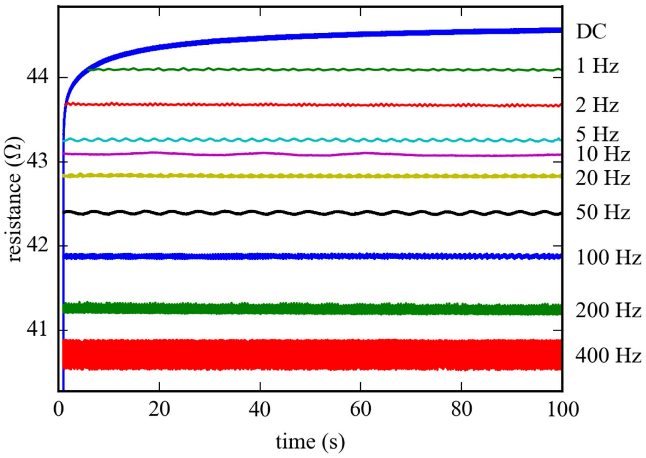

Figure 4. Time-based comparison of traditional DC resistance and the proposed biphasic DC measurement method using a 50% duty cycle and 9 varying sensing current frequencies, annotated on the right-hand side of the figure.

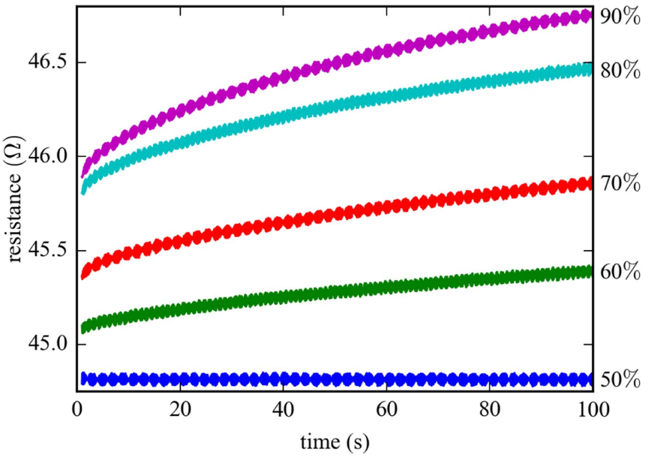

Figure 5. Time-based comparison of changing duty cycles, annotated on the right-hand side of the figure, for a sensing current frequency of 20 Hz.

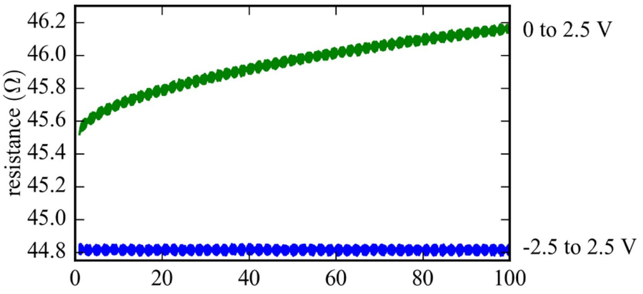

Figure 6. Time-based comparison of a sensing current (20 Hz) ranging from 0 to 2.5 V, in comparison to a sensing current ranging from −2.5 to 2.5 V.

multi-channel resistance measurements of a multi-sectioned sample.

4.1. Reductions in sensor drift

Time series comparison between a DC resistance measurement and the proposed biphasic DC measurement approach for various sensing current frequencies is presented in figure 4. At a test time of one second, the sensing voltage is applied to the fully discharged specimen. As expected, the DC resistance measurement experiences a sharp increase in the observed resistance in the first few seconds and begins to level out as time increases. In comparison, the proposed biphasic DC measurement technique provides a constant resistance measurement, with its measured resistance value depending on the frequency of the applied sensing current. It is hypothesized that lower frequencies measure a higher resistance because the material has more time for polarization, resulting in an apparent increase in resistance. The level of variation in the measured resistance value (noise) increases with an increase in sensing frequency. Possible causes for this increase in noise are investigated at the end of this section.

The effects of reducing the discharge time on resistance stability is inspected next. A reduction in the discharge time is obtained through an increase in the duty cycle of the sensing current, therefore allocating more time into the sensing current's measure region than into its discharge region. Figure 5 presents the effects of changing duty cycles on a 20 Hz signal. A 20 Hz sensing current was used to obtain a sampling rate (20 S/s) capable of tracking the high levels of drift found in the first few seconds of testing. As the duty cycle increases, i.e. the amount of time the sensing current spends in the measurement region of the cycle, the biphasic measurement method starts to drift upward in a manner similar to that observed with DC measurement. The authors propose that this 'drift' is a function of the sensing current spending insufficient time in its discharge region during each cycle, resulting in the self-sensing material being not fully discharged.

Complete discharging requires that the sensing current is fully reversed to reset the material polarization effects. Figure 6 shows the drift present if an alternating sensing current ranging from 0 to 2.5 V is applied, in comparison to a sensing current ranging from −2.5 to 2.5 V. Without the reversal in sensing current provided by the −2.5 V, the self-sensing material drifts upward. Again, it is proposed that this drift is a product of the sensor not being fully discharged by a non-reversing current. A 2 Ω difference is present between the nominal resistance found in the 20 Hz test for the results presented in figure 4 and those found in figures 5 and 6. This difference conceivably results from a change in the laboratory temperature, as the tests were conducted on different days and the resistivity of carbon-doped cement matrices is strongly dependent on temperature [28].

4.2. Strain sensitivity

The ability of the biphasic measurement approach to function for strain-sensing characterization is presented here. First, the cement paste cube, presented in figure 1(a), is tested in a quasi-static compressive loading test using a sensing frequency of 1 Hz and voltage ranging from −2.5 to 2.5 V with a duty cycle of 50%. Sensor characterization results are

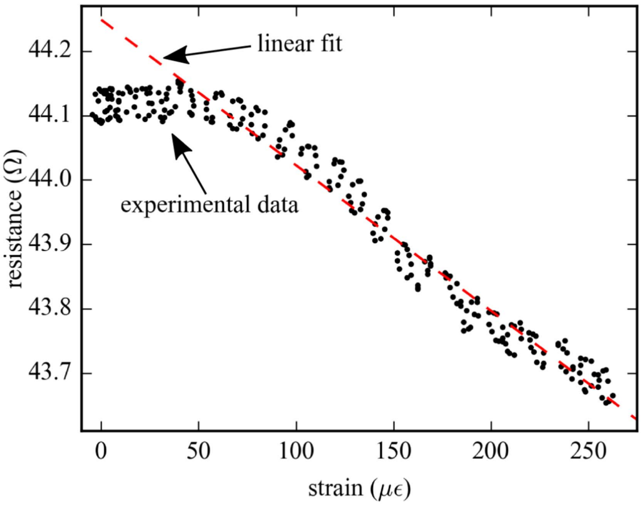

Figure 7. Strain-resistance characterization for MWCNT cement-based sensor using the biphasic measurement approach.

presented in figure 7 plotting the value of the calculated resistance as a function of the measured strain. The load is applied in increments of 0.1 kN and held for approximately 45 seconds at each loading step. It total, 26 loading steps, ranging from fully unloaded to 2.5 kN, were performed. The loading induced strain is measured with resistive strain gauges (RSGs) adhered onto the surface of the specimen. An approximately linear portion of the sample specimen was found between 0.6 and 2.5 kN, after the material locking phenomenon is fully activated, relating to a measured strain of 60–260 $\mu\varepsilon$ in the cement paste specimen. It is noted that the ability of the nanocomposite material in exhibiting changes in internal resistance under an applied deformation is driven by deformation-induced changes in electrical interactions between nanoparticles [35]. The resulting relationship between electrical resistance and strain can exhibit some degree of nonlinearity, as in the low deformation range of figure 7, but a linear assumption is typically acceptable for deformation ranges of interest in civil engineering, as it is the case in figure 7 after a pre-loading inducing a strain of 60 $\mu\varepsilon$. For this reason, the authors assumed a linearity between measured resistance and strain, and resistance values are calculated using equation (3) as presented above. The linear portion of the test specimen is annotated with a red line between 60 and 260 $\mu\varepsilon$. The sensor response for the 20 loading cases ranging from 0.6 to 2.5 kN reports a linear relationship between the measured strain and resistance. As expected, the specimen's resistance decreases as the force is applied, resulting in a sensitivity of 0.002 $\Omega/\mu\varepsilon$. The consistency of the gauge factors for a similarly sized sample of high conductivity presented in [18] demonstrates that the proposed biphasic DC measurement technique does not reduce the specimens strain-sensing ability. The same test could not be carried out with standard DC measurement approach due to the time drift observed in figure 4 for the DC case.

The ability of the biphasic measurement approach to monitor strain over a range of sensing current frequencies is presented in figure 8. Again, sensitivity was calculated in the assumed linear range from 60 to 260 $\mu\varepsilon$. While small variations in the sensitivity are reported, the trend is still strongly linear, with the drift quantified as 0.84% change over the total range as shown by the line of best fit. These results indicate the ability of the biphasic measurement approach to monitor strain-sensing materials' strain state over a range of sensing current frequencies, further expanding the versatility of the method.

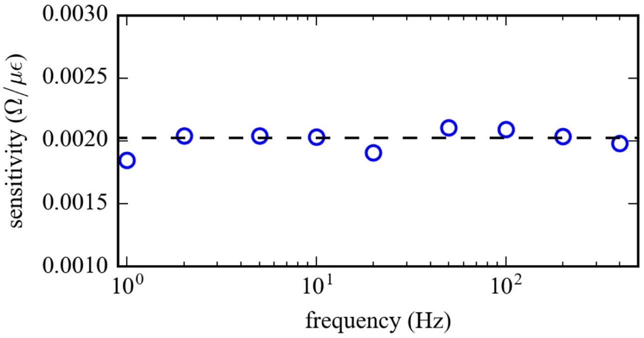

Figure 8. Strain sensitivity as a function of applied sensing current.

4.3. Dynamic strain measurement

The biphasic DC measurement approach's ability to monitor specimen's dynamic strain induced resistance is presented here. The cube specimen was again used for strain testing and is presented in figure 9. A sinusoidal compressive load ranging from 0.6 to 1.6 kN was applied over 50 cycles for each mechanical loading. For the mechanical loading of 1 Hz, the RSG strain data is shown if figure 9(a) and the specimen's measured resistance using a sensing current frequency of 200 Hz is presented in figure 9(b). A sensing current frequency of 200 Hz was selected to obtain a high sample rate of 200 S/s to effectively capture the sensor's dynamic response. The resistance data was then filtered using a first-order order Butterworth low-pass filter with a cutoff frequency of 50 Hz to eliminate the power line frequency noise. The filtered data is also presented in figure 9(b). Lastly, the biphasic DC measurement response over the mechanical loading range of 1–6 Hz is investigated. For each loading case, the RMS value for the 50 cycles was obtained for both the RSG and resistance data for the self-sensing specimen. A strain sensitivity of 0.002 $\mu\varepsilon/\Omega$ was then applied to the resistance data to obtain a strain value. The sensor's frequency response curve for $\varepsilon_{\text{specimen}}/\varepsilon_{\text{RSG}}$ is presented in figure 9(c). Results show that the biphasic DC measurement approach is capable of providing dynamic strain data for the mechanical frequency range of 1–6 Hz while retaining a linear sensitivity over the investigated frequency range. It is noted that the use of a standard DC measurement approach would cause a drift in the signal of figure 9(b) that would require a high pass filter to be removed. Previous work by the authors [17] showed that a cutoff frequency of 5 Hz is typically needed for this purpose, what would limit the measurement frequency range of the sample in figure 9(c) to the range beyond 5 Hz.

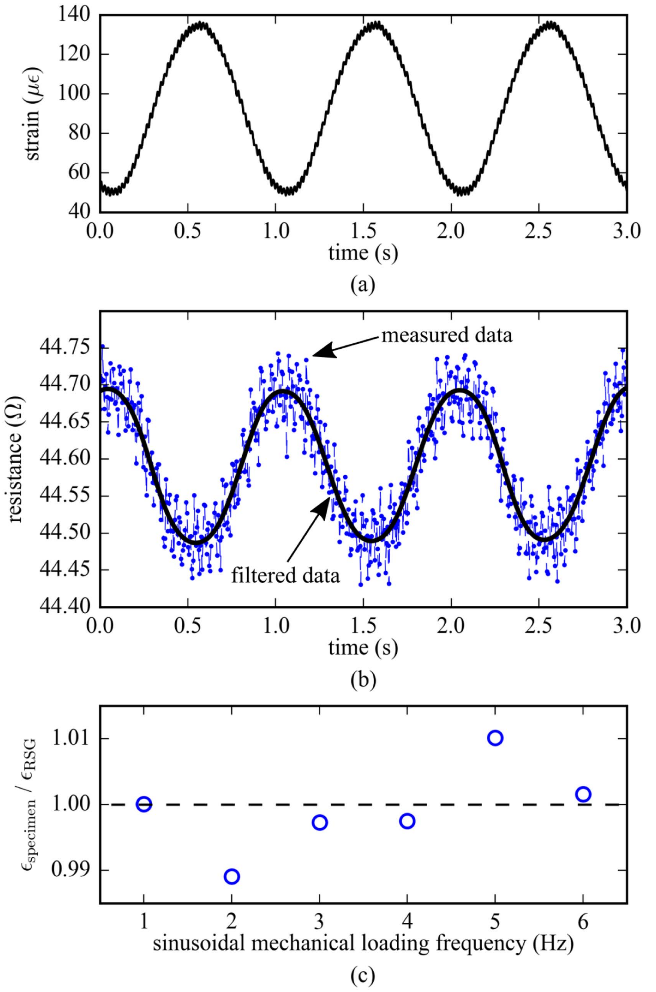

Figure 9. Dynamic strain measurement for a sinusoidal mechanical loading: (a) strain measured with RSG for a 1 Hz mechanical loading frequency; (b) biphasic DC resistance measurement taken at 200 S/s; (c) strain response for $\varepsilon_{\text{specimen}}/\varepsilon_{\text{RSG}}$ for mechanical loading frequencies in the range 1–6 Hz.

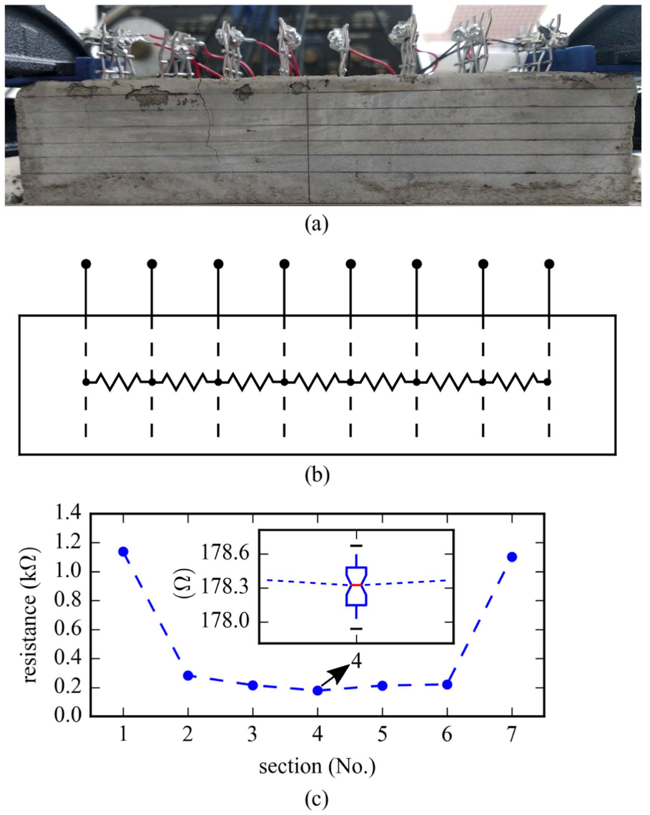

Figure 10. Simultaneous, multi-channel measurement of self-sensing cement paste specimen sectioned into 7 sections: (a) beam specimen sample with embedded contacts; (b) resistor model for sectioned beam; and (c) experimental data measured using a 1 Hz sensing current with signal noise shown as a box plot in the inserted figure.

4.4. Simultaneous multi-channel measurement

Here, the ability of the biphasic measurement approach to function as a simultaneous, multi-channel measurement technique for self-sensing structural material is validated. The beam specimen presented in figure 1(b) is tested as diagrammed in figures 3(c), (d). A 1 Hz sensing current is used to provide a low level of noise. For calculating sectioned resistance values, a simple resistance element model was developed and is presented in figure 10(b) where each section is divided into a simple resistor, ignoring complex interactions between non-adjacent sections. Figure 10(c) presents the measured resistance values for the beam, while the distribution of the 100 samples taken at section 4 are in the form of a boxplot in the figure's insert. The noise present in the biphasic measurement approach, while not insignificant, does not affect its ability to measure the individual resistance values of a multi-sectioned specimen [36]. The high resistance values in the extremity sections are the results of the contact resistance that are only present in the current carrying contacts [16]. The biphasic resistance measurement results presented here demonstrate that the biphasic measurement approach is capable of the simultaneous monitoring of multi-sectioned self-sensing materials and offers the potential for material properties verification, damage detection and localization. The investigation of these opportunities is beyond the scope of this introductory work.

4.5. Noise investigation

The noise present in the resistance measurement, as observable in figure 4, has been demonstrated to increase with an increase in the frequency of the applied sensing current. Expanded views of the variations in the sample resistance measurements are presented in figures 11(a)–(c) for 1, 20 and 400 Hz. Variations in the selected resistance measurements are repeatable and consistent as shown in figures 11(a)–(c). While the magnitude of the noise increases with an increase in the applied frequency, the noise present in each applied sensing current frequency maintains a repeatable pattern. Results for other sensing current frequencies are similar but are not shown for conciseness. This repeatability in the measurement noise is assumed to be a function of varying sources. First, the 50 Hz noise present in the signal generator output and its interaction with the frequency of the sensing

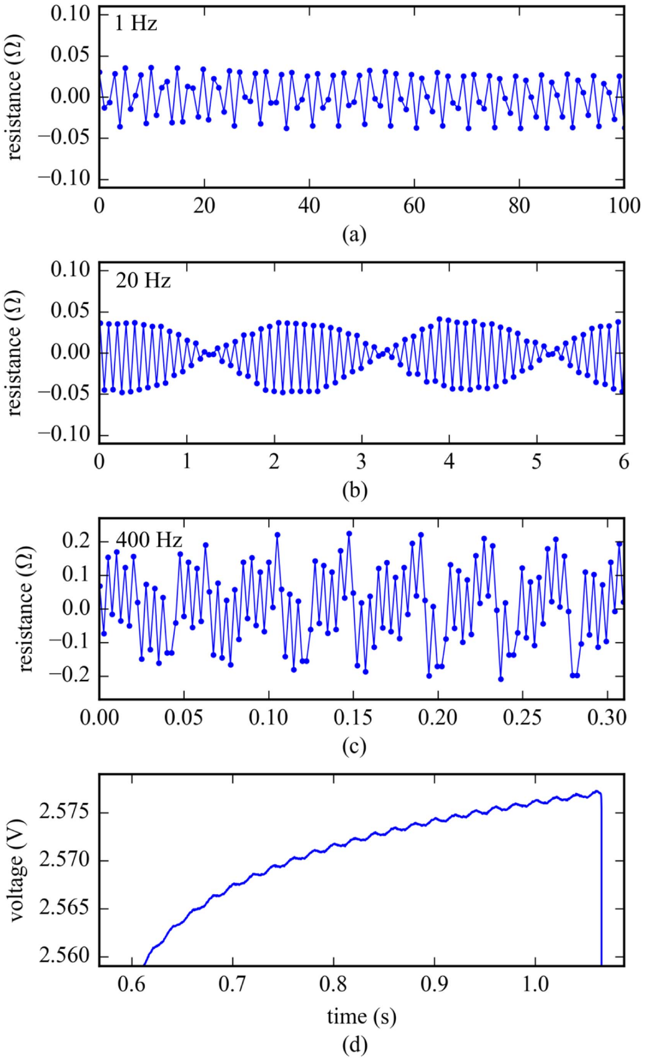

Figure 11. Inspection of resistance values for sensing current frequencies of: (a) 1 Hz; (b) 20 Hz; (c) 400 Hz, taken at 50% duty cycle; and (d) 50 Hz noise present in the measure portion of the 1 Hz applied square wave.

current is assumed to make a large contribution to the repeatable variations in the measured resistance noise. The mains noise present in the applied voltage can be seen in figure 11(d), that is an expanded view of the data previously presented in figure 2. Secondly, the DAQ's sampling rate was held constant at 5000 S/s for all tests. This means that sensing currents with lower frequencies benefited from a higher number of samples per cycle, therefore allowing measurements consistently closer to the 80% mark as denoted in figure 2. For example, a 1 Hz sensing current has a total of 2500 samples in the measurement portion of the signal resulting in the closet sample being no more than ±0.04% away from the 80% mark as defined above. In comparison, a 400 Hz signal has on average 6.25 samples per measurement cycle meaning that for a measurement cycle containing only six samples, the closest sample may be up to ±8.33% away from the 80% mark. Lastly, the carbon-based material's interaction with the sensing current has been found to induce a non-trivial level of noise into the measurements [33]. The sources of noise and their complex interactions need to be further studied. The use of dedicated electronics may greatly reduce the noise level of the proposed biphasic measurement approach. However, the noise present in the current experiments does not preclude the possibility of measuring very small strains and most likely will not impede damage detection.

5. Conclusion

This work proposed and reported on an electrical measurement approach that is better suited for use in the resistance measurement of self-sensing multi-functional structural materials for SHM applications. The proposed measurement approach consists of applying a periodic measure/discharge signal in the form of an alternating square wave. DC measurements are made during the signal's measurement region while material depolarization is obtained during the discharge region of the periodic signal. Resistance values for the self-sensing structural material are obtained by dividing the measured voltage by the current flow through the specimen. The measurement approach provides a consistent measurement technique for self-sensing structural materials that greatly reduces the effect of sensor drift caused by material properties. This drift has been well documented in multiple carbon-based structural materials and is often attributed to material polarization, to changes in the material's dielectric constant, to the direct piezoelectric effect, or to complex interactions between multiple effects, such as double layer capacitance effects around electrodes and around conductive inclusions. The biphasic measurement approach is capable of providing a discharging of the self-sensing structural material and, therefore, measurements taken over time can be compared. The proposed measurement approach enables the simultaneous, multi-channel acquisition of adjacent sections in a sectioned self-sensing structural material. This further increases the versatility and deployment opportunities of the proposed measurement approach.

A comparison between the proposed biphasic DC measurement approach with DC resistance measurement was presented using a self-sensing structural material specimen, consisting of MWCNTs suspended in a cement paste matrix. The biphasic DC measurement approach was capable of providing a constant resistance measurement, resulting from the material being fully discharged during each measurement cycle. It was demonstrated that drift returned to the sensor measurement if the duty cycle was altered away from 50% or the sensing current never reversed the direction of flow. These results demonstrate that a self-sensing structural material needs to be fully discharged to obtain a reduction in drift. The same specimen was then characterized over a range of static strains, demonstrating the proposed biphasic measurements approach's ability to monitor strain-sensing materials.

The proposed biphasic DC measurement approach shows great improvement over a traditional DC measurement technique for use with carbon-based self-sensing structural materials through its reduction of sensor drift. Additionally, the proposed measurement method is well suited for the simultaneous measurement of multi-sectioned self-sensing materials in comparison to various AC measurement techniques. Effects of various measurement parameters, including applied voltage and frequency over a range of temperatures, need to be investigated with respect to noise and sensitivity. However, these effects are material-based and beyond the scope of this introductory work.

The proposed novel measurement technique shows great promises for a range of self-sensing structural materials, in both civil and aerospace structures. With prolonged static measurements, self-sensing carbon-based structural materials could be used to monitor an engineered system's health. Multichannel acquisition can allow for damage detection and localization in large-scale deployments of self-sensing structural materials. Examples of applications for self-sensing structural materials in civil infrastructure include the use of sensors integrated into building columns, bridge girders and pylons, or to develop smart mortars and smart bricks for masonry structures. Examples for the benefit of aircraft and wind turbine blades could be the implementation of smart wing spars or self-monitoring shells for prolonged SHM. Furthermore, smart materials could be deployed for rapid condition assessment of civil infrastructure after natural or man-made hazards.

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