Low-Cost Biphasic DC Data Acquisition for Monitoring Cementitious Self-Sensing Materials

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ABSTRACT

Self-sensing materials possess the capability to monitor their own conditions, offering promising solutions for structural health monitoring (SHM) in civil and mechanical infrastructure. By altering the matrix properties of materials through doping with fillers such as carbon fibers, carbon black, and multiwall carbon nanotubes, these materials exhibit piezoresistive behavior. This enables the measurement of electrical properties like impedance, capacitance, and resistance, which correlate with the material's structural health. However, DC measurements often reveal a time-based drift in resistance due to material polarization. This work presents hardware developments for a biphasic data acquisition system to address the phenomenon of drift. The system leverages the theory that the drift in carbon-based self-sensing materials is due to material polarization, mitigated by reversing the excitation current direction. This approach effectively eliminates observable drift, ensuring accurate SHM assessments.

Keywords: self-sensing materials, structural health monitoring, data acquisition, resistance, biphasic, carbon fillers

1. INTRODUCTION

Self-sensing materials demonstrate a unique ability to monitor their own conditions.[1] They are often presented as a solution to the challenges of structural health monitoring (SHM) within civil infrastructure and mechanical applications.[2] Alterations or additions to a material's matrix-level properties allow it to adopt characteristics that allow for qualitative observation through electrical signals. Doping of cement-based materials with fillers like carbon fibers, carbon black, carbon nanotubes, and other conductive materials has shown to be effective in establishing piezoresistive and sensing behavior at the matrix-filler interaction level. Such cement-based materials can be easily exploited to measure their impedance,[3] capacitance,[4] or resistance,[5] enabling rapid evaluation of the structural health of a material.

Measurements are often made using direct current (DC) to obtain the aforementioned electrical parameters. While the use of DC has proven to be a useful means of yielding self-sensing material electrical characteristics, it tends to introduce a time-based drift in the output of the material. This drift, representing itself as a steady increase in resistance starting from the time the measurement begins, is commonly attributed to material polarization,[6] changes in the material's dielectric constant,[7] or a direct piezoelectric effect.[8] Numerous researchers have sought to address material drift by comparing sensing materials with control samples,[9] material compensation,[10] or by postponing measurements until the drift stabilizes (e.g.,[8, 11, 12]). Although this method may be effective for dynamic measurements, it is less appropriate for static measurements.

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A solution to address the issue of drift exploits the theory that the drift present in carbon-based self-sensing materials is an intrinsic material property caused by the polarization of the material as a function of the time an excitation current is applied. This polarization is shown to be fully dependent on the direction of the excitation current flow as the material itself is not intrinsically polarized. The effect of polarization can be fully negated by reversing the direction of the sensing current, thus eliminating the drift observed as a result of the material's polarization. Leveraging this knowledge, the authors previously proposed the biphasic DC measurement approach in Downey et al.[13] The biphasic DC measurement method utilizes a periodic square wave excitation current with a 50% duty cycle. The positive portion of the signal is termed the measure phase, while the negative is termed discharge. This measure/discharge cycle is employed to achieve stable and consistent resistance measurements for self-sensing structural materials. Resistance is measured during the measurement phase of the square wave, while material depolarization occurs during the discharge phase (i.e. reversed current flow). Experimental results demonstrate that this technique effectively eliminates signal drift in carbon-based self-sensing materials and allows for simultaneous multi-channel measurements of multi-sectioned self-sensing materials.[14] The biphasic DC measurement has been used successfully for the integration of self-sensing bricks,[15] asphalt, and cementitious materials,[16] lime-based composites,[17] and sustainable construction materials such as earth-based ones.[18]

In this work, a low-cost portable data-acquisition system is presented that implements the biphasic DC measurement approach into a package designed for the continuous monitoring of self-sensing materials using a standardized hardware design. The hardware is introduced and tested for sampling rates of 1, 2, and 5 Hz. The hardware design is open-sourced.[19] The contribution of this work is the advancement of SHM by introducing a low-cost, portable, and open-sourced data acquisition system that employs the biphasic DC measurement method to ensure stable, consistent, and simultaneous multi-channel resistance measurements in self-sensing materials.

2. APPLICATIONS IN MONITORING STRUCTURES

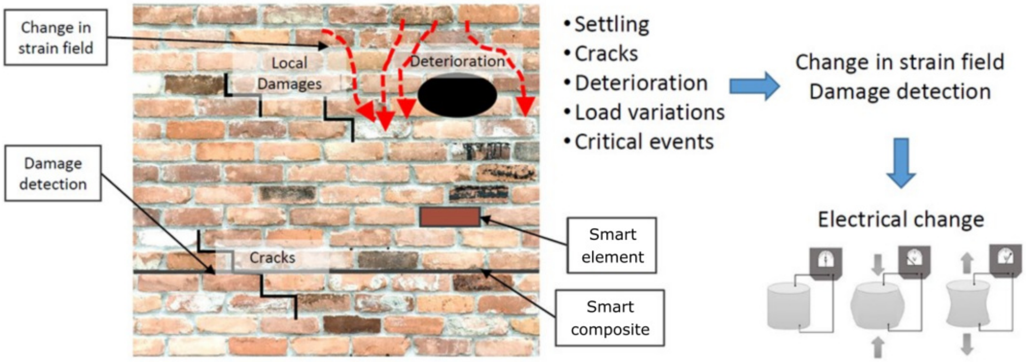


Figure 1. Representation of the sensing behavior and damage detection of smart construction materials

SHM systems can be employed to evaluate the structural performance of existing constructions in real-time, to improve the safety of both buildings and their occupants. Continuous monitoring can detect early changes in parameters like strain and displacement, which may indicate the beginning of crack formation and potential collapse mechanisms as shown in Figure 1. This is particularly crucial for existing structures, such as masonry ones, which are prone to brittle damage. Additionally, historical structures often suffer from material degradation over time, resulting in reduced strength to withstand service loads and seismic events. The preservation of existing structures, particularly important for historical ones, needs the development of a non-invasive, continuous, simple, and economical monitoring system, capable of operating in real-world conditions.

3. METHODOLOGY

This section introduces the methodology, starting with the biphasic measurement approach, followed by an introduction to the hardware and the experimental methodology used.

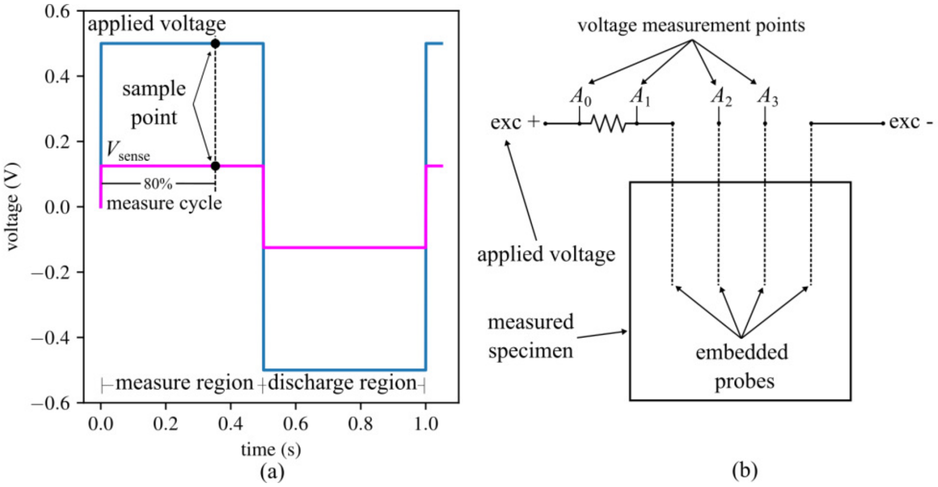


Figure 2. Overview of the biphasic sensing approach, showing the: (a) excitation current in the form of a 1 Hz square wave with a 50% duty cycle demonstrating the configuration of the measure and discharge regions along with sample points for the applied and sensing voltages, and; (b) a simplified circuit diagram for a smart material specimen with embedded probes that diagrams the key connections required for four probe biphasic measurement.

3.1 Measurement approach

The biphasic DC measurement approach is detailed in Downey et al.[13] and the key points are highlighted here for brevity. The biphasic DC measurement approach is shown in Figure 2 and consists of a square wave with a 50% duty cycle fed to the specimen where DC voltage measurements are taken precisely 80% through the measurement region of the square wave. The discharge region can be interpreted as a reverse polarization phase, preventing the accumulation of charge that can affect resistance calculation. The resistance of the material is determined by measuring the voltage drop across a known resistor in series with the material. By dividing this voltage drop by the resistor's value, the system calculates the current flowing into the material. Subsequently, an analog-to-digital (ADC) measurement is taken across two probes embedded in the material to obtain the voltage, which is then divided by the calculated current to yield the material's resistance.

The current flowing into the material, $i_{\text{calculated}}$, is determined by the voltage drop ($V_{\text{drop}} = A_0 - A_1$) across a known resistor $R_{\text{in-line}}$ as follows:

$$i_{\text{calculated}} = \frac{V_{\text{drop}}}{R_{\text{in-line}}} \tag{1}$$

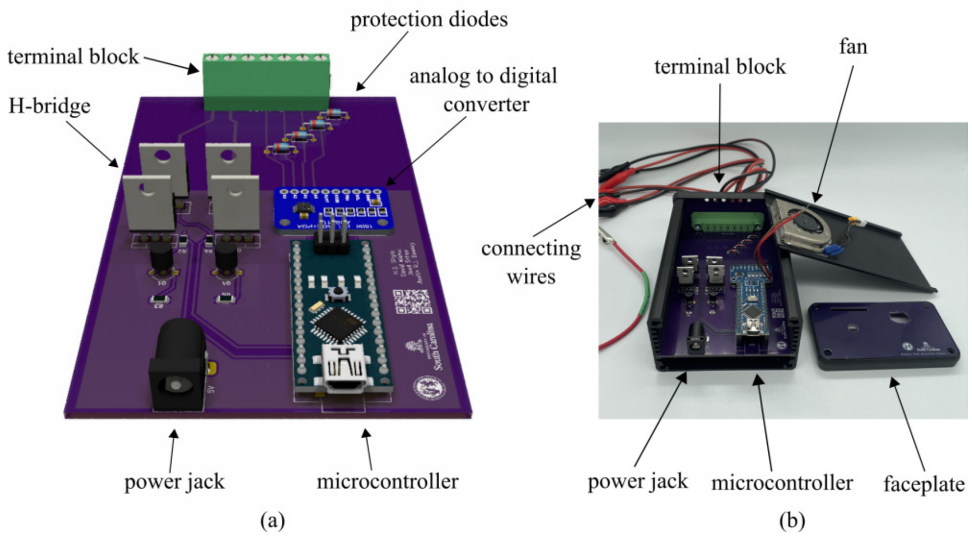
The resistance R of the material is then calculated by measuring the voltage V_{sense} across two probes ($V_{\text{sense}} = A_2 - A_3$) embedded within the material and using the calculated current $i_{\text{calculated}}$:

$$R = \frac{V_{\text{sense}}}{i_{\text{calculated}}} \tag{2}$$

The sampling rate of the measurements is directly correlated to the frequency of the square wave, as data is collected only at the 80% point of the measurement phase. Figure 2(b) depicts a four-probe measurement approach, a two-probe measurement approach can be achieved by connecting A_2 to A_1 and connecting A_3 to exc -.

3.2 Data acquisition

The biphasic DC data acquisition system is comprised of a custom printed circuit board (PCB) with a host microcontroller used to interface with external hardware. The hardware design is open-sourced.[19] The microcontroller chosen was the ATmega328P utilized within the Arduino framework; specifically the Arduino Nano. The Arduino Nano was selected for its low power consumption, small form factor, and abundance of internal hardware timers used for precise synchronization of the state of the excitation current and timing of measurements. The microcontroller is responsible for the generation of the excitation current and ensuring the ADC is active only during the appropriate time within the measurement region of the excitation current. The design of the system can be generalized into two primary components, the generation of the excitation current and the analog acquisition of the material's electrical properties.



(a) (b)

Figure 3. The biphasic DC data acquisition system, showing a: (a) 3D CAD model of the system and; (b) photograph of the system placed in a protective case.

Generating the biphasic DC excitation current involves providing the H-bridge in the system with a switching signal from the microcontroller. The software was developed utilizing hardware timers in the microcontroller to prompt the H-bridge switching signal. Such timers ensure the precision and consistency of the excitation current's duty cycle. The use of an H-bridge provides the system with the capability of easily producing an excitation current of differing polarity. The output of the H-bridge, whose traces lead to two separate pins in the terminal block, are connected directly to probes exc + and exc - protruding from the cementitious material; as shown in Figure 2(b).

Taking measurements of the material's electrical properties involves the use of an analog-to-digital converter (ADC) to measure the voltage across the material. The ADC selected for the system was the ADS1115, a 16-bit ADC with four channels. The ADS1115 features an ability to operate in either single-ended or differential mode, with the latter being the chosen configuration. Two of the four channels are used to measure the voltage drop across a resistor of known value, yielding V_{drop} and $R_{\text{in-line}}$ from equation 1. The remaining channels are used to measure the voltage across the material, corresponding to V_{sense} from equation 2. Protection diodes are used to safeguard the ADC from voltage spikes that may occur during the measurement process.

3.3 Experimental Procedure

To assess the effectiveness of the biphasic DC data acquisition system, measurements were taken from a sample of sef-sensing material doped with carbon nanotubes. To determine the value of the known resistor, $R_{\text{in-line}}$, to be used, repeated measurements using a multimeter were taken across the probes of the sample, grounding the sample between each measurement by connecting the probes together for thirty seconds to remove any residual charge. The resistance of the sample was reported to be around 220 kΩ. A 220 kΩ wire-round resistor was selected for the current sensing resistor. The sample was then connected to the system and measurements were taken over a period of 10 minutes at frequencies of 1 Hz, 2 Hz, and 5 Hz. One measurement utilizing a pure 5 V DC excitation current was also collected to be compared against the use of biphasic DC. The data was collected and stored on a computer for further analysis.

4. RESULTS

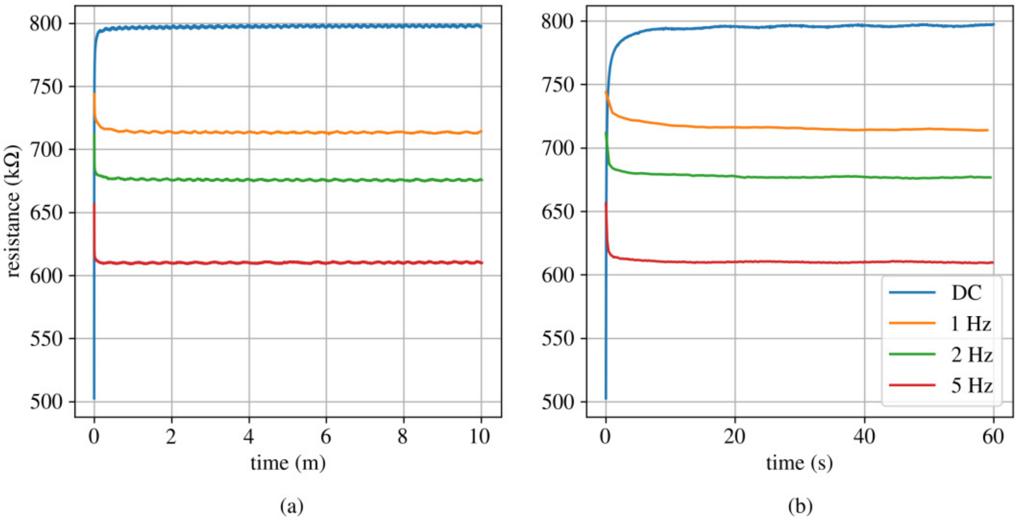


Figure 4. Result of the acquisition performed with the ~ 220 kΩ self-sensing material over a duration of: (a) 10 minutes and; (b) 60 seconds

The acquired resistance data shown in Figure 4 demonstrates the effectiveness of the biphasic DC data acquisition system in mitigating drift. One can observe in Figure 4 a dramatic but brief change in resistance at the beginning of each acquisition. This is attributed to polarization in the material during system initialization, caused by the H-bridge providing the sample with an excitation current not assuming an entirely inactive state.

Following the brief period of material polarization, the resistance values obtained using frequencies of 1 Hz, 2 Hz, and 5 Hz remain consistent and stable throughout the duration of the acquisition, demonstrating the system's ability to eliminate drift. The system's performance was further validated by comparing the resistance values obtained using the biphasic DC approach to those obtained using a pure DC excitation current, the latter exhibiting drift easily seen in Figure 4. The results indicate that the biphasic DC data acquisition system is effective in mitigating drift in resistance measurements of self-sensing materials.

The limitations of the system primarily follow the limitations of the H-bridge design chosen for generating the excitation signal. The previously mentioned brief period of material polarization at the beginning of each acquisition is still under investigation but is suspected to be a result of subthreshold conduction. This phenomenon occurs when, in the context of N-channel devices, the MOSFET gate-to-source voltage is below its specified threshold voltage, but not low enough to fully turn off the component, resulting in a small flow of current across it. This issue can be addressed by ensuring the gate voltage for NMOS components is below the threshold voltage, and above the threshold voltage for PMOS components.

5. CONCLUSION AND DISCUSSION

This study presents a low-cost, field-deployable biphasic DC data acquisition system designed to mitigate drift in resistance measurements of self-sensing materials. The biphasic DC measurement approach effectively eliminates drift, demonstrated for materials with resistances ~ 220 kΩ; however, it must be acknowledged that these results are particular to this system. The open-source hardware design ensures accessibility and cost-effectiveness, making it widely adoptable by the research community. This system has significant implications for the preservation and safety of cultural heritage structures, allowing for early detection of structural changes and preventing catastrophic failures. Future research should explore methods to address drift in high-resistance materials and validate the system's performance in various environmental conditions.

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