A Single Carbon Nanotube-paper Composite Electrode Sensor Based Brake Oil Degradation Detection

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A BSTRACT

Brake oil is essential to the performance and safety of hydraulic braking systems, but its degradation—primarily caused by water absorption—can lead to reduced boiling points, corrosion, and brake failure. This study presents a non-invasive method for real-time monitoring of brake oil degradation by detecting changes in water content using a single-electrode capacitive sensor based on a carbon nanotube paper composite (CPC). The sensor operates on the principle of fringing electric fields, enhanced by high-aspect-ratio carbon nanotube fibers that increase local field intensity and dielectric sensitivity. Unlike conventional two-electrode designs, this configuration offers structural simplicity and is well-suited for embedded automotive platforms. Experimental testing was conducted using two types of brake fluids, with incremental additions of deionized water (0.5% by volume) to simulate moisture-induced degradation. The sensor exhibited a strong linear response to increasing water concentration, with consistent slopes across fluid types, enabling a generalized calibration model for real-time water content estimation. The CPC sensor demonstrated high sensitivity, fast response, and excellent repeatability, making it an effective solution for in-situ brake fluid monitoring. This work supports the development of predictive maintenance systems aimed at improving vehicle safety and operational reliability.

1. INTRODUCTION

Brake fluids are critical for ensuring the safe operation of hydraulic braking systems in modern vehicles. Their primary function is to transmit force from the brake pedal to the wheel cylinders, allowing for controlled deceleration. Most commercially available brake fluids are inherently hygroscopic; they readily absorb moisture from the surrounding environment over time (Kao et al., 2006). This water absorption is a significant concern for long-term vehicle performance and safety, as it leads to boiling point depression, corrosion of brake system components, and formation of gas bubbles under high-temperature conditions, resulting in a dangerous phenomenon known as vapor lock (Hunter et al., 1998).

Studies have shown that as little as 2% water content in brake fluid can reduce the wet boiling point to below 45°C, potentially causing brake failure in high-demand conditions such as mountain descents or emergency stops (Ibrahim & Petrík, 2024). Despite its importance, routine brake fluid testing is often neglected due to the lack of easy-to-use, embedded diagnostic tools. Traditional methods for oil degradation monitoring rely on laboratory-based measurements such as viscosity testing (kinematic viscometers), total acid number (TAN) and total base number (TBN) analysis, dielectric constant evaluation, and particle counting which require non-situ sample collection and analysis, limiting their suitability for real-time monitoring (Zhu et al., 2013). These constraints highlight the need for reliable, low-cost, and real-time sensing mechanisms that can operate non-invasively within a vehicle's braking system.

In this context, capacitive sensing offers a promising approach, as it can detect subtle dielectric property changes in fluids due to water contamination. The dielectric constant of pure brake fluid typically ranges from 5 to 10, while water has a much higher dielectric constant of approximately 80. This large contrast enables sensitive detection of moisture ingress. However, most existing capacitive sensors employ parallel plate configurations that require immersion in the fluid and are often bulky or difficult to integrate into constrained automotive environments.

To overcome these limitations, this study introduces a single-electrode capacitive sensor based on CPC. This novel design utilizes fringing electric fields that extend into the surrounding fluid, enabling contactless dielectric sensing. The inclusion of high-aspect-ratio carbon nanotube fibers along the sensor's perimeter enhances local electric field intensity and sensitivity, allowing for accurate detection of even small changes in water content. Unlike traditional sensors, the CPC design is structurally simple, flexible, and compatible with embedded automotive systems.

2. EXPERIMENTAL SETUP

The core component of the capacitive sensing system is a CPC electrode, fabricated using multi-walled carbon nanotubes (MWCNTs) embedded in cellulose fibers. MWCNTs were selected due to their optimal dimensional properties. They are long enough to form effective conductive pathways, yet short enough to allow uniform and stable coating on the cellulose substrate. In addition to their electrical properties, MWCNTs offer advantages in terms of cost and ease of processing, especially in water-based fabrication methods. These characteristics make them more suitable for scalable sensor manufacturing than alternative materials such as silver nanowires.

To prepare the CPC, MWCNTs were suspended in water using a surfactant and deposited onto cellulose fibers, where they formed stable interactions with the hydroxyl groups of the cellulose, resulting in strong bonding. A circular sensor geometry (13 mm nominal diameter) was chosen to promote a uniform fringing electric field distribution. The wet CPC material was shaped using a wet-fracture punching technique, which involved compressing the wet composite between a die and punch system to form circular electrodes with fibrous, high-aspect-ratio edges. Figure 1 shows fabricated CPC sensor.

These individualized fibers around the CPC perimeter played a critical role in enhancing the local electric field strength and sensitivity. A low-density, high-aspect-ratio fibrous perimeter helped generate intense fringing fields, which are essential for detecting small changes in the dielectric environment. Following the punching process, silver ink was screen-printed to define the sensing electrode on one side of the CPC disc. The opposite side was prepared with a water droplet to pre-wet the surface and maintain consistent fluid contact.

As shown in figure 2, the fabricated CPC electrode sensor was electrically interfaced with a high-resolution capacitance-to-digital converter (CDC) via a low-noise, active shielding coaxial cable to minimize parasitic capacitance and external electromagnetic interference. This configuration enabled accurate acquisition of low-level capacitive signals generated by the sensor in response to changes in the dielectric environment. The CPC sensor and its interfacing electronics were mounted securely above a transparent glass plate, ensuring mechanical stability and electrical isolation during measurements.

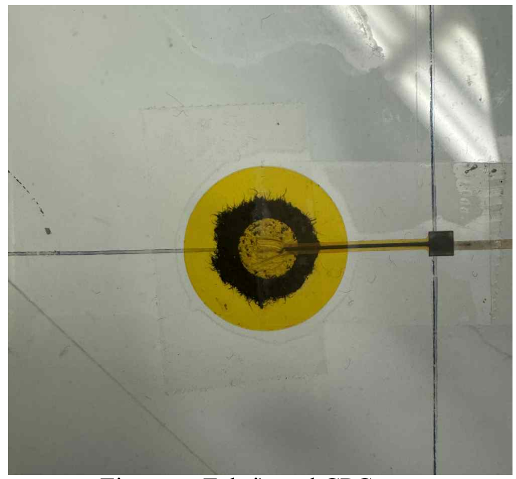

Figure . Fabricated CPC sensor.

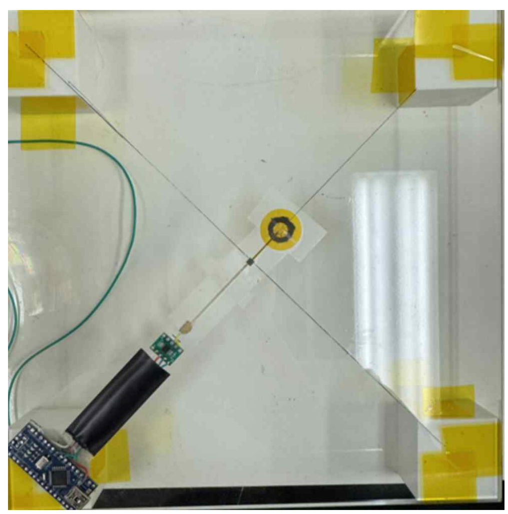

Figure 2. Top view of the sensor platform setup.

As shown in figure 3, plastic beaker containing 200 mL of brake fluid was positioned above the sensor such that the CPC electrode was aligned with the base of the fluid container, enabling strong interaction between the sensor's fringing electric field and the brake fluid without direct immersion. This arrangement was designed to simulate a practical, non-invasive sensing configuration suitable for integration into embedded automotive systems.

Two types of brake fluids were evaluated independently under identical test conditions. To simulate degradation due to environmental moisture increase, water was incrementally added to each fluid sample in precise 1 mL steps, representing 0.5% increases in water concentration by volume. This controlled addition continued until a final water content of 4.0% reached.

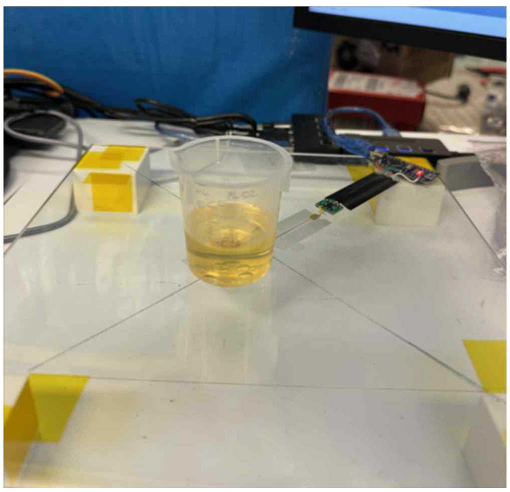

Figure 3. Side view of water percentage experiment setup.

Capacitance readings were captured continuously in real time through the CDC and transmitted to a host computer for digital logging and analysis. For each water contamination volume, 15 seconds of capacitance data were collected. The acquired data for each interval was time-averaged to obtain a representative capacitance value corresponding to the specific volumetric concentration of water added to the brake fluid. The resulting dataset that comprising discrete capacitance values mapped to known water content levels served as the input for the development of a predictive degradation model based on linear regression For both brake fluid types, an individual linear regression model was computed using least-squares fitting, yielding a slope and intercept that characterized the sensor's response to increasing water concentration.

3. RESULTS

The CPC capacitive sensor demonstrated a strong and repeatable linear response to incremental increases in water content in both brake fluid samples. As water was added in 0.5% volumetric steps (1 mL increments in 200 mL total fluid), corresponding shifts in the measured capacitance were observed in real time. Each 15-second interval of continuous data acquisition produced a time-averaged capacitance value, minimizing measurement noise and transient fluctuations. Capacitance response to incremental water percentage is shown in figure 4.

Linear regression analysis was performed independently for each brake fluid type, yielding highly linear fits. The resulting models took the standard form of:

$$y = mx + c \qquad (1)$$

Where y is the averaged capacitance value (pF), x is the water concentration (%), m is the slope representing sensor sensitivity and c is the baseline capacitance of the fluid with 0% water concentration.

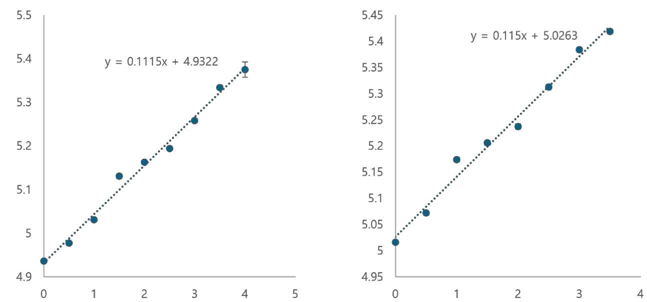

Figure 4. Capacitance response to incremental water percentage.

While the intercept values, c, varied between the two brake fluid types due to differences in their baseline dielectric constants, the slopes, m, of the regression lines were found to be highly consistent, indicating that the rate of capacitance change per unit water concentration is largely independent of the base fluid composition. This enabled the development of a generalized degradation model by computing the average slope from both regression analyses. This unified slope value was adopted as a constant sensitivity coefficient for reverse calculation of water content.

In practical applications, the sensor will be first initialized with clean (dry) brake fluid. The capacitance recorded at this state will be stored as the intercept c. As the system operates, the sensor will continuously capture real-time capacitance readings y. The percentage of water contamination x will then be computed by rearranging the linear model.

4. CONCLUSION

This study demonstrated a novel, non-invasive method for real-time monitoring of brake fluid degradation using a single-electrode capacitive sensor fabricated from a CPC. The sensor utilizes high-aspect-ratio multi-walled carbon nanotube fibers embedded in cellulose to enhance fringing electric fields, enabling highly sensitive detection of dielectric changes caused by water contamination in brake fluid. Through a cost-effective and scalable fabrication process, circular CPC sensors with fibrous perimeters were produced and interfaced with a CDC for accurate, low-noise data acquisition.

Experimental validation was performed using two types of brake fluids under controlled conditions, with water incrementally added to simulate real-world degradation. The sensor exhibited a consistent and highly linear capacitive response to increasing water concentration, confirming its suitability for precise, quantitative condition monitoring. The linear regression models derived from the experimental data revealed fluid-type-specific intercepts but nearly identical gradients, enabling the formulation of a generalized degradation model with a unified sensitivity coefficient.

Importantly, this model allows the reverse calculation of water concentration from real-time capacitance measurements using the equation $x = \frac{y - c}{m}$, where c is the initial baseline capacitance measured upon installation with clean brake fluid.

The CPC sensor system offers key advantages such as high sensitivity, structural simplicity, fast response, and low power requirements, making it an ideal solution for predictive maintenance in braking systems. By enabling early detection of moisture-induced degradation, this technology has the potential to enhance vehicle safety, reduce maintenance costs, and support the development of intelligent automotive diagnostics.

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