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ADVANCED NOZZLE DIAGNOSIS IN INTERNALLY GENERATED WAVEFORM PRINTHEADS

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Abstract

The demand for inkjet printing continues to grow across industries, driven by its flexibility and ability to deliver high-quality output at high speeds. However, ensuring reliability remains a challenge, as nozzle performance is affected by multiple factors such as ink properties, mechanical integrity, and electrical stability. Failures at the nozzle level, even if localized, can significantly compromise print quality.

Printheads driven by analog waveforms have traditionally offered more flexibility and lower internal complexity, which makes them more accessible for the implementation of sensing techniques. By contrast, digital printheads, while advantageous for standardization and integration, require the development of new sensing methods and advanced algorithms to extract, process, and classify nozzle information.

This work demonstrates novel approaches for real-time nozzle monitoring in digital printheads. By analyzing variations in the electrical and acoustic signatures of the nozzles, it becomes possible to identify a wide range of failure modes such as air entrapment, electrical malfunction, or mechanical degradation. The capability to detect and classify nozzle states opens new opportunities for predictive maintenance, reduced downtime, and improved reliability and print quality.

Introduction

Piezoelectric drop-on-demand (DoD) inkjet printheads have become ubiquitous in precision manufacturing sectors, ranging from printed electronics to textile functionalization. Despite their widespread adoption, they remain susceptible to stochastic process variations that can critically alter jetting performance [1]. Operational reliability is contingent upon the real-time detection of nozzle failures, which may stem from diverse root causes such as particulate clogging, air entrapment (priming failure), or structural electrical faults within the actuator assembly [2, 3]. If left undiagnosed, these anomalies invariably lead to production defects, material waste, and costly downtime.

From an electrical architecture perspective, industrial printheads are generally classified into two categories: those driven by externally generated waveforms and those with internally generated waveforms [1, 4]. Architectures utilizing externally generated waveforms facilitate 'self-sensing' capabilities by allowing the direct measurement of residual acoustic waves from the piezoelectric actuator after drop ejection [2, 3, 5]. However, many high-throughput industrial systems increasingly favour architectures with internally generated waveforms. In these systems, waveform generation, digital-to-analog conversion, and power amplification are embedded directly within the printhead's Application-Specific Integrated Circuit (ASIC) [4]. This high level of integration effectively renders the printhead a 'black box', obscuring direct physical access to the piezoelectric actuator pins and rendering traditional acoustic monitoring methods—which rely on direct piezo sensing impossible [6].

Currently, monitoring strategies for these integrated systems are predominantly limited to analysing the static supply current (average power consumption). While this approach is effective at detecting catastrophic failures—such as short circuits or driver thermal shutdowns—it lacks the temporal resolution and sensitivity required to identify subtle hydraulic anomalies [3, 7, 8]. For instance, a nozzle suffering from air ingestion often presents a nominal average electrical load, resulting in false negatives during standard diagnostic routines. The static analysis masks the transient variations in current that occur during the microsecond-scale actuation of the piezo crystal [2, 3].

This paper presents a novel methodology for inferring nozzle status in printheads with internally generated waveforms by exploiting the coupling between electrical consumption and mechanical impedance in the time domain [5]. The fundamental hypothesis is that the piezoelectric actuator acts as a bidirectional transducer; consequently, the mechanical impedance of the fluidic chamber—modulated by factors such as the presence of ink, fluid viscosity, or obstruction—directly influences the instantaneous charging current drawn from the high-voltage supply rail [8]. By analyzing differential current consumption under specific non-jetting 'probe waveforms', we demonstrate the ability to distinguish between electrical failures (open/short circuits), nominal firing conditions, and specific hydraulic issues, effectively eliminating the need for external optical sensors [3, 7, 5].

Methodology and Experimental Setup

To validate the proposed non-invasive monitoring technique, a dedicated test bench was developed to control the printhead, acquire real-time power consumption data with high temporal resolution, and systematically simulate various failure modes.

System Architecture

The experimental setup utilizes a Seiko Instruments RC1536 industrial printhead, a widely used model featuring an architecture with internally generated waveforms. Unlike printheads where the waveform is generated externally and fed directly to the piezo, this unit manages piezoelectric actuation internally via digital commands. This internal management necessitates an indirect monitoring method, as the individual actuator nodes are not accessible.

To monitor the internal state without modifying the printhead hardware, a high-side current sensing circuit was implemented on the high-voltage supply rail (V_{pp}), as illustrated in Figure 1. The sensing element is a precision low-inductance shunt resistor placed in series with the printhead's power input. The voltage drop across this resistor is directly proportional to the instantaneous total current drawn by the internal drivers and the charging cycles of the piezoelectric actuators.

The acquisition system is driven by a 600MHz ARM Cortex-M7 microcontroller, which serves the dual purpose of generating the printing data/signals and managing the synchronization of the sensing logic. The analog signal from the current sensor is digitized using an LTC2315CTS8, a high-speed 12-bit Analog-to-Digital Converter (ADC). This specific ADC was selected to ensure sufficient temporal resolution to capture the fast transient current features (charging and discharging slopes) during waveform actuation.

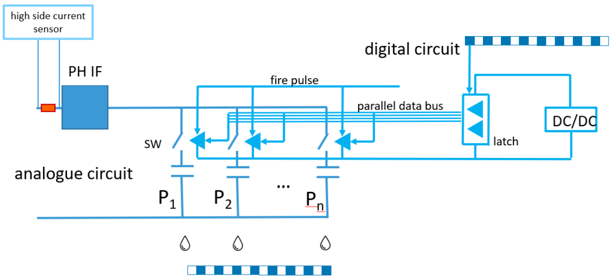

Figure 1. *Simplified schematic of the high-side current sensing setup. The current sensor captures the aggregate load of the active piezoelectric channels ($P_1 \ldots P_n$) driven by the internal digital circuit and DC/DC converters.*

Fluidic Control and Test Materials

Strict control of hydraulic parameters is essential to isolate acoustic effects from environmental noise. The fluidic system regulated the meniscus pressure to stable operating conditions. The pressure at the nozzle inlet ($P+$) was maintained at 3 mbar, while the outlet pressure ($P-$) was set to -15 mbar, resulting in a net meniscus pressure ($P_{meniscus}$) of -6 mbar. The recirculation flow rate was approximately 65 mL/min to ensure consistent thermal distribution.

For the experimental fluid, a standard cleaning liquid ("CleanJet") provided by *People & Technology* was utilized. The fluid temperature was actively controlled at 34° C. This specific fluid was chosen to eliminate variables related to pigment sedimentation while maintaining rheological properties relevant to industrial inkjet applications. As shown in Figure 2, the complex viscosity norm $|\eta^*|$ of the fluid decreases slightly with frequency, stabilizing around $3.5-4.5$ mPa·s in the relevant acoustic range.

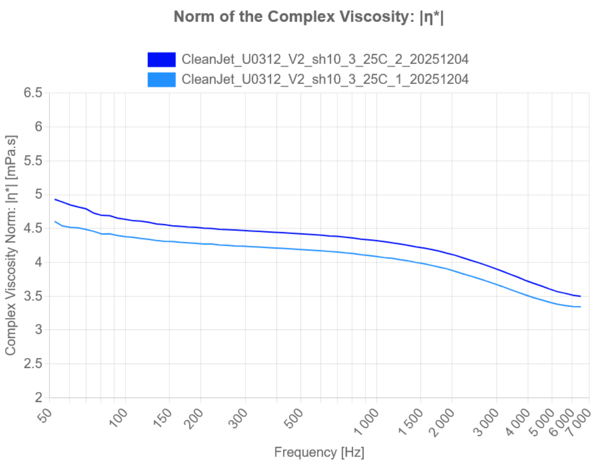

Figure 2. *Norm of the complex viscosity $|\eta^*|$ of the test fluid (CleanJet) as a function of frequency at 25° C. The fluid exhibits shear-thinning behavior typical of inkjet formulations.*

Probe Waveform and Frequency Sweep

A critical component of this methodology is the design of the excitation signal. The methodology relies on "Differential Current Analysis," triggering a firing sequence using specific "Probe Waveforms". These waveforms are designed not necessarily for optimal printing quality, but to maximize the acoustic resonance response of the nozzle chamber while keeping the fluid meniscus stable.

The excitation parameters for the probe waveform were defined as follows: a Drive Voltage amplitude of 15 V, a Pixel Clock of 10 kHz, and a burst of approximately 6 repetition pulses. The amplitude of 15 V was selected as a "sub-threshold" voltage—sufficient to induce mechanical oscillation in the piezo and fluid, but low enough to prevent drop ejection. This protects the substrate and allows for diagnostic cycles without ink consumption.

Furthermore, to fully characterize the mechanical impedance of the system, a frequency sweep was performed. By varying the actuation frequency and analyzing the current response at each step, we reconstructed the impedance spectrum of the nozzle. This spectral analysis allows for the identification of resonance shifts caused by hydraulic variations such as clogging (which changes the effective mass) or air entrapment (which changes the compliance).

Defect Classification

The study utilized a set of printheads categorized into three distinct groups to test the sensitivity of the differential current analysis:

- **Reference Group:** Fully functional nozzles used to establish the baseline current signature ($I_{baseline}$).
- **Electrical Failure Group:** Printheads containing nozzles with known electrical discontinuities. These defects were induced by applying excessive mechanical force to the nozzle plate, resulting in internal circuit disconnections (simulating "Open Circuit" failures).
- **Hydraulic Failure Group:** Printheads with electrically intact connections but compromised jetting performance. These failures were attributed to fluid incompatibility and controlled clogging, representing the "Black Box" scenario where the electrical check passes, but the nozzle fails to jet.

Results

The experimental results show distinctive electrical signatures for different failure modes and operating conditions, validating the hypothesis that mechanical impedance modulates the power supply current.

Electrical Failure Characterization

Three reference levels were established based on the amplitude of the current amplifier signal. As observed in the load characterization shown in Figure 3, a functional nozzle presents a nominal peak signal of ≈ 0.48 V. A "Half Load Failure" decays significantly to an intermediate level (≈ 0.38 V), indicating a partial loss of capacitance or connectivity in the piezoelectric actuator stack. Finally, a "No Load" or total electrical failure remains flat at ≈ 0.27 V, indicative of a total open circuit where no current charges the piezo.

Applying this analysis to a full printhead scan ("Electrical Test"), a severe anomaly was detected in Row C. While Rows A, B, and D maintain a stable current in the 0.8 mA range, Row C shows critical dispersion. As visualized in Figure 4, one group of nozzles presents "half load" values and another extensive group

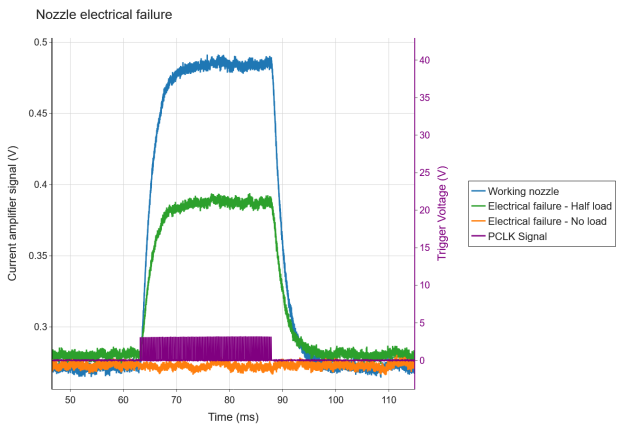

Figure 3. *Signal level characterization. Note the distinct voltage plateaus for functional nozzles (blue), half-load failures (green), and open circuits (orange).*

shows values close to zero (total failure). This distribution suggests a progressive structural damage in that specific row, likely due to delamination or a driver bank failure.

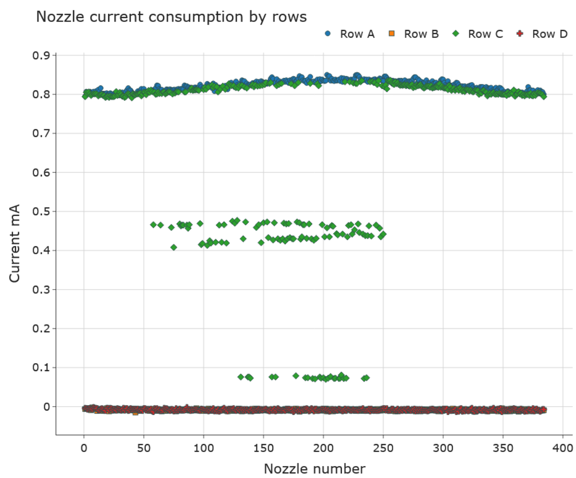

Figure 4. *Full electrical test results across all nozzles. The bimodal failure distribution in Row C (green diamonds) indicates progressive structural damage compared to the healthy Rows A, B, and D.*

This electrical degradation correlates visually with print tests where missing lines are observed in the test pattern, as evidenced in Figure 5.

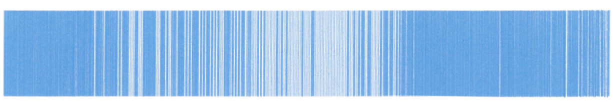

Figure 5. *Nozzle check pattern. The missing print lines correspond directly to the nozzles identified as "No Load" failures in the electrical test.*

Sensitivity to Fluidic Loading

The system demonstrated sensitivity to the presence of ink in the pumping chamber. Comparing the same nozzle (Nozzle 1200) under two different conditions reveals the impact of acoustic damping. With ink, the nozzle showed a peak current consumption of 0.84 mA. Under identical firing conditions but without ink (Dry), the peak consumption reduced to ≈ 0.77 mA.

This difference of approximately 0.07 mA validates that the electrical impedance of the piezoelectric element is measurably affected by the acoustic load of the fluid. The fluid acts as a mechanical load; removing it reduces the work required by the piezo actuator, resulting in a lower current draw. Figures 6 and 7 illustrate this amplitude shift.

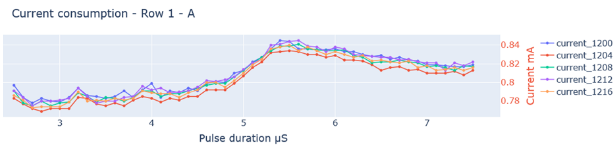

Figure 6. *Current consumption with fluidic loading (Ink present). Peak current reaches ≈ 0.84 mA.*

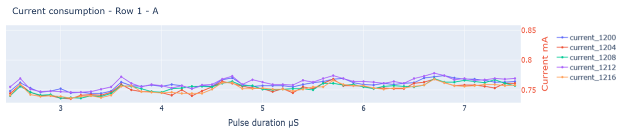

Figure 7. *Current consumption without ink (Dry). Note the reduction in peak amplitude to ≈ 0.77 mA due to lack of the mechanical impedance of the fluid.*

Clogging Detection

The analysis of nozzles in Row B reveals unstable current traces for nozzles 62, 66, and 70 (Figure 8). These nozzles exhibit variations in rise time and erratic peak amplitudes compared to the consistent signatures of healthy nozzles. This behavior evidences an alteration in the system's resonance frequency caused by the obstruction, which disrupts the regular fluidic oscillation and changes the instantaneous load on the piezo.

Figure 8. *Current trace variations for clogged nozzles in Row B. The instability and timing shifts in the waveform serve as a signature for partial clogging.*

This diagnosis was validated through a printed nozzle check pattern. As shown in Figure 9, the physical print confirms that nozzles 62 and 66 are failing to eject ink. This direct correlation confirms that the unstable electrical signatures detected by the system correspond to actual jetting failures caused by clogging or hydraulic instability.

Figure 9. *Visual confirmation of jetting failure. The highlighted regions show missing lines corresponding to nozzles 62 and 66, which correlate with the unstable electrical traces.*

Discussion & Conclusion

The high-side current sensing methodology has proven to be a robust, non-invasive tool for the comprehensive diagnosis of printhead health (Health Monitoring). By analyzing the power supply signature, this approach successfully overcomes the limitations of purely visual tests and the accessibility constraints inherent to "black box" integrated driver architectures.

A critical advancement demonstrated in this study is the ability to distinguish between varying degrees of structural failure, specifically "Half Load" and "No Load" conditions. The bimodal distribution observed in Row C provides specific insight into the failure mechanism: the "No Load" signature correlates with catastrophic mechanical damage to the piezoelectric actuator, likely induced by excessive external force applied to the nozzle plate. This mechanical stress results in a fracture of the piezo actuator, manifesting electrically as an open circuit. Unlike transient hydraulic issues, this specific signature indicates a permanent, irreversible failure, allowing operators to immediately disqualify the printhead without further testing.

Significantly, the results validate the theoretical principle that the piezoelectric actuator acts as a bidirectional transducer sensitive to its hydraulic environment. The measured reduction in current ($\approx 8-9\%$) between a wet and dry nozzle confirms that priming failures are detectable electronically. Beyond immediate jetting failures, we posit that this methodology holds significant potential for detecting long-term degradation caused by physicochemical incompatibility between the ink and printhead materials. Specifically, aggressive ink formulations may degrade internal structural adhesives, leading to nozzle stack delamination and a consequent loss of chamber pressure. Since the system is highly sensitive to mechanical impedance changes, it is theoretically capable of identifying the subtle acoustic shifts associated with this structural compliance change before visible leakage occurs.

From a signal processing perspective, a fixed calculation window was employed across all waveforms, specifically configured to capture the stationary region of the current consumption profile. Due to the significant decoupling capacitance present at the printhead's power rail input, initial charging transients obscure the piezoelectric load signature. Consequently, it was necessary to sustain the firing sequence for approximately 15 ms to allow these transients to dissipate and reach a steady-state consumption. Furthermore, the adoption of a dedicated 'non-jetting' probe waveform—characterized by a 15 V amplitude and 10 kHz frequency—proved essential. By operating strictly below the voltage threshold required for drop ejection, this configuration maximizes the acoustic resonance response for impedance analysis while ensuring that no ink is deposited on the substrate during the diagnostic process.

In conclusion, the proposed system allows for real-time characterization ranging from structural electrical integrity to subtle fluid dynamic conditions. By enabling the detection of both permanent mechanical failures and developing hydraulic anomalies, this methodology paves the way for predictive maintenance and closed-loop reliability control in high-throughput industrial inkjet systems.

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Author Biography

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