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An Energy-Efficient 3.7-nV/$\sqrt{\text{Hz}}$ Bridge Readout IC With a Stable Bridge Offset Compensation Scheme

Hui Jiang, Student Member, IEEE, Stoyan Nihtianov, Senior Member, IEEE, and Kofi A. A. Makinwa, Fellow, IEEE

Abstract—This paper describes an energy-efficient bridge readout IC (ROIC), which consists of a capacitively coupled instrumentation amplifier (CCIA) that drives a continuous-time delta–sigma modulator (CT$\Delta$ΣM). By exploiting the CCIA’s ability to block dc common-mode voltages, the bridge’s bias voltage may exceed the ROIC’s supply voltage, allowing these voltages to be independently optimized. Since bridge output is typically much smaller than bridge offset, a digital to analog converter (DAC) is used to compensate this offset before amplification and thus increase the CCIA’s useful dynamic range. Bridge loading is reduced by using a dual-path positive feedback scheme to boost the CCIA’s input impedance. Furthermore, the CCIA’s output is gated to avoid digitizing its output spikes, which would otherwise limit the ROIC’s linearity and stability. The ROIC achieves an input-referred noise density of 3.7 nV/$\sqrt{\text{Hz}}$, a noise efficiency factor (NEF) of 5, and a power efficiency factor (PEF) of 44, which both represent the state of the art. A pressure sensing system, built with the ROIC and a differential pressure sensor (AC4010), achieves 10.1-mPa ($1\sigma$) resolution in a 0.5-ms conversion time. The ROIC dissipates about 30% of the system’s power dissipation and contributes about 6% of its noise power. To reduce the sensor’s offset drift, a temperature compensation scheme based on an external reference resistor is used. After a two-point calibration, this scheme reduces bridge offset drift by 80$\times$ over a 50 °C range.

Index Terms—Beyond the rails, bridge offset compensation, bridge sensor, capacitively coupled (CC) chopper, CC instrumentation amplifier (CCIA), continuous-time delta–sigma modulator (CT$\Delta$ΣM), energy efficient, readout IC (ROIC), temperature compensation.

I. INTRODUCTION

WEATHERSTONE bridges are widely used to read out impedance sensors that monitor physical parameters such as temperature, pressure, and humidity [1]–[12]. As shown in Fig. 1, their output can be digitized by a readout IC (ROIC), which consists of an instrumentation amplifier (IA) and an analog to digital converter (ADC). To maximize the accuracy of the resulting sensing system, the ROIC should have low input-referred noise, low-temperature drift, high input impedance, high linearity, and high common-mode rejection ratio (CMRR) [2], [13]. It should also have high energy efficiency to facilitate its use in battery-powered applications and in precision mechatronic systems where self-heating may be an issue [14].

An ROIC’s energy efficiency will usually be determined by its IA, since this sets its input-referred noise. Recently, capacitively coupled (CC) IAs have been shown to be particularly energy efficient [3]. As shown in Fig. 2, a CCIA consists of an input chopper, which up-modulates differential input voltages to a chopping frequency, $f_{\text{chop}}$, allowing them to be amplified by an inverting amplifier with capacitive feedback elements. Since they only require one noise-critical input stage, CC IAs are generally more energy efficient than three-Opamp and current-feedback (CF) IAs [15]. Moreover, their input capacitors naturally block common-mode (CM) input voltages, allowing them to handle CM levels much larger than their supply voltages [4]. In bridge readout applications, this means that the bridge and the ROIC can be powered from different voltage supplies, allowing the ROIC’s supply voltage to be optimized for energy efficiency. Last but not the least,
since CCIAs are inherently chopped, their $1/f$ noise and offset are also quite low.

A major drawback of CCIAs is that they generate output spikes at their chopping transitions, i.e., at $2f_{chop}$ [3]. These should not be digitized since their amplitude is usually not a linear function of the input signal. In the case of a discrete-time ADC, this can be readily achieved by sampling the output of the CCIAs just before the chopping transitions [3]. The CCIAs bandwidth then needs to be wide enough to ensure complete settling, which increases noise aliasing and thus degrades the ROIC’s overall energy efficiency [5]. Furthermore, the ADC’s sampling frequency $f_s$ is now the same as $2f_{chop}$, which limits design flexibility. In [6], a dynamic filter has been used to limit the noise bandwidth while maintaining settling accuracy, but at the expense of increased design complexity.

This paper describes a pressure sensing system that consists of an energy-efficient ROIC and a bridge-type pressure sensor [16]. The ROIC uses a gated continuous-time delta–sigma modulator (CTΔΣM) to digitize the CCIAs output while avoiding its output spikes. To maximize the CCIAs useful dynamic range, the bridge offset is compensated by a passive digital to analog converter (DAC) referred to the bridge biasing voltage. This ratio-metric approach ensures that the compensating signal only depends on capacitor and resistor ratios, and so is stable over temperature and bias voltage variations. Implemented in a standard CMOS 180-nm process, the ROIC achieves a state-of-the-art noise efficiency factor (NEF) of 5. It dissipates about 30% of the system’s power and contributes about 6% of its noise power, resulting in a resolution of 10.1 mPa (rms) with a range of ±100 Pa in a 0.5-ms conversion time.

The rest of this paper is organized as follows. Section II discusses the main techniques used in the ROIC to achieve high energy efficiency and high precision. Section III describes the implementation details of the ROIC and pressure sensing system with temperature calibration are presented in Section IV. Section V provides the conclusion.

II. SYSTEM DESIGN OF THE ROIC

Differential pressure sensors with a range of ±100 Pa are required in air gages for industrial applications [7]. The AC4010 is a high-resolution bridge-type piezo-resistive pressure sensor that can cover this range. To achieve a resolution of 10 mPa (rms) over 1-kHz bandwidth, its biasing voltage $V_{bias}$ should be at least 5 V, thus resulting in a sensitivity of about 45 $\mu$V/Pa. However, this will be superimposed on a bridge offset of about 100 mV, due to the mismatch of its piezo-resistive elements (nominally 3.7 k$\Omega$ each), to ensure that the ROIC does not limit the sensor’s performance, it should be designed to meet the specifications in Table I.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input noise density</td>
<td>4 nV/√Hz (~1 kΩ)</td>
</tr>
<tr>
<td>Conversion time</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Input CM level</td>
<td>2.5 V</td>
</tr>
<tr>
<td>Input range</td>
<td>±100 mV (offset), ±10 mV (signal)</td>
</tr>
<tr>
<td>Gain</td>
<td>≈100</td>
</tr>
<tr>
<td>Input impedance</td>
<td>&gt;370 kΩ (for &lt;0.1% gain error)</td>
</tr>
<tr>
<td>Offset drift</td>
<td>&lt;10 $\mu$V/°C</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>&lt;6.8 mW</td>
</tr>
<tr>
<td>INL</td>
<td>&lt;50 ppm</td>
</tr>
</tbody>
</table>

One way of avoiding this tradeoff is to exploit the beyond-the-rails capability of a CCIAs. As shown in Fig. 3(a), the bridge can then be powered from a 5-V supply, while the ROIC can be powered from a 1.8-V supply voltage. The only active components exposed to the bridge’s 2.5-V CM voltage are the switches of the CCIAs CC input chopper [Fig. 3(b)], which can be realized with deep n-well CMOS (DMOS) transistors or I/O devices [18]. The CCIAs input capacitors can be implemented by metal–insulator–metal (MIM) capacitors, which, in most processes, are capable of handling even higher voltages.

B. Compensating the Bridge Offset

Due to bridge mismatch, however, increasing $V_{bias}$ will also increase bridge offset. Since this can be quite large, it will limit the IA’s useful output range, and hence its gain. As a result, the succeeding ADC will need to have a wider dynamic range and lower input-referred noise, both of which will result in increased power dissipation.

To avoid this problem, bridge offset should be compensated before amplification. This can be done by using: 1) an external offset compensation network to trim the bridge [19] and 2) a current DAC to inject a programmable current into the bridge [20]. However, the bridge and the compensation...
circuitry will inevitably have different temperature dependencies, leading to significant temperature drift.

In this paper, the CCIA is used to implement a ratio-metric offset-compensation scheme (Fig. 4). The bridge output $V_{in}$ is added to an offset-compensating signal generated by a capacitive DAC (CDAC$_1$), which is referred to $V_{bias}$ via a resistive divider. By implementing both $C_{in}$ (input capacitor of the CCIA) and CDAC$_1$ with MIM capacitors, both the bridge output $V_{in}$ and the divider’s output $kV_{bias}$ will respond in the same way to temperature and $V_{bias}$ variations.

Note that the residual bridge offset and bridge sensitivity will still drift over temperature. As shown in Fig. 1, such errors can be absorbed by an overall system calibration. However, the proposed bridge offset compensation minimizes the errors contributed by the ROIC, ensuring that the overall system accuracy is mainly limited by the bridge sensor.

### C. Dual-Path Input Impedance Boosting Scheme

A known drawback of CCIA is that they output spikes at twice the chopping frequency ($2f_{chop}$) [3]. This is because $C_{in}$ must be rapidly charged and discharged at the chopping transitions. To reduce the amplitude of these spikes, most of the required charge can be provided from the output of the CCIA via a positive feedback path [3] or by an auxiliary pre-charge path [6], which also boosts the CCIA’s input impedance. Although the boosting effect of a positive feedback path is limited by parasitic capacitors and stability considerations [3], it is more appealing in this design, as a pre-charge path requires active buffers which would compromise the CCIA’s beyond-the-rails capability.

As shown in Fig. 4, a positive feedback path can be realized with an extra capacitor $C_{pf}$ which should provide a compensation charge $Q_{com}$ [3], given by

$$Q_{com} = C_{pf}V_{out} \approx C_{in}V_{in} = Q_{in}$$  \hspace{1cm} (1)$$

where $V_{in}$ consists of two parts, the useful bridge signal $V_{sig}$ and the bridge offset $V_{off}$. However, in the proposed design (Fig. 4), $V_{off}$ will be partially canceled by CDAC$_1$ before amplification. To still provide a charge proportional to the compensated offset, a capacitive DAC (CDAC$_2$) is added, and driven by the same code as CDAC$_1$. The total compensation charge is now given by

$$Q_{com} = C_{pf}V_{out} + Q_{DAC} \approx C_{in}(V_{sig} + V_{off}) = Q_{in}. \hspace{1cm} (2)$$

### D. Gating the Output of the CCIA

The CCIA’s residual output spikes can be avoided by using a discrete-time $\Delta \Sigma$ modulator (DT$\Delta \Sigma$M) to synchronously sample the CCIA’s output. The modulator’s sampling frequency $f_{s}$ will then be equal to $2f_{chop}$, as shown in Fig. 5(a) [3, 5]. Assuming that the CCIA is a single pole system without slew rate limitations, a minimum bandwidth $BW$ is needed to achieve sufficient settling [21]

$$BW \geq 2 \cdot (m + 1) \cdot f_{s} \cdot \ln 2 \hspace{1cm} (3)$$

where $m$ is the target resolution of the ROIC in bits. Due to the sampling process, noise within a bandwidth of $\pi/2\cdot BW$ will fold back to baseband, increasing the CCIA’s in-band noise power density. This significantly decreases the ROIC’s energy efficiency [5]. A dynamic RC filter can be used to limit the noise bandwidth before sampling [Fig. 5(b)] at the expense of increased design complexity [6].

In this design, the CCIA’s residual spikes are avoided by gating the input of a $CT\Delta \Sigma M$ [4]. As shown in Fig. 5(c), the input of the $CT\Delta \Sigma M$ is connected to the CM voltage for the duration of the spikes, after which it is connected to the output of the CCIA. In this way, the errors associated with the CCIA’s spikes are reduced without noise fold back. Compared to a switched-capacitor (SC) load, the resistive load presented by the modulator significantly relaxes the requirements on the CCIA’s driving capability and thus further improves the ROIC’s energy efficiency. Since the CCIA’s output is effectively duty cycled, these benefits are acquired at the expense of a small reduction (2.5%) in its effective gain.
III. ROIC IMPLEMENTATION DETAILS

A simplified circuit diagram of the proposed ROIC is shown in Fig. 6. It consists of a CCIA with bridge offset-compensation circuitry and a gated CTΔΣM. In this section, the implementation of these blocks will be discussed in detail.

A. CCIA

The gain of the CCIA is set at 40 dB. To achieve high linearity, the CCIA is built around a two-stage Miller compensated amplifier, with a dc gain of about 124 dB. The bridge has an equivalent source resistance of 3.7 kΩ, corresponding to a noise density of 7.8 nV/√Hz. The CCIA’s input-referred noise should then be lower than this, which is quite challenging. The first stage consists of a chopped folded-cascode amplifier with a very large PMOS input pair (1280 μm/0.2 μm) that is biased in weak inversion to efficiently realize a trans-conductance of about 6.7 mS. As shown in Fig. 7, the input pair consuming most of the current of the amplifier. To mitigate the noise gain penalty due to the input pair’s parasitic capacitance (1.3 pF), the CCIA’s input capacitors $C_{in}$ were set to 10 pF [3].

In this design, the offset and 1/f noise of the 1st stage is mitigated by chopping, while that of the 2nd stage is suppressed by the gain of the 1st stage. Often [2], [22], and [23], the demodulating chopper (drawn with dotted lines in Fig. 7) is located at nodes A and B and C and D. In this case, the cascodes are not chopped and their 1/f noise becomes dominant, as shown in Fig. 8(a).

This can be addressed by moving the chopper to the output of the 1st stage, i.e., nodes E and F in Fig. 7. As shown in Fig. 8(a), chopping at 200 kHz results in a simulated 3.2 mHz 1/f noise corner. However, the chopped parasitic capacitors ($C_{p1,2}$) at these nodes will form an SC resistance, which, in turn, will reduce the gain of the 1st stage. To mitigate this, the cascode transistors were made relatively small ($M_7,8$: 24 μm/1.8 μm and $M_9,10$: 60 μm/1.2 μm), and the layout was optimized. In this way, chopping only reduces the open-loop gain by 2 dB [Fig. 8(b)].

To minimize their noise contribution, the CCIA’s bias resistors $R_b$ should be in excess of 250 MΩ. To conserve area, they are implemented as SC resistors to achieve good linearity and stability over process and temperature variations [18]. The input chopper consists of capacitively driven DMOS transistors, allowing the input of the CCIA to handle bridge CM voltages up to 3.3 V (limited by the ESD-protection diodes) while operating from a 1.8-V supply.

B. Offset Compensation DAC

The bridge offset-compensation circuit consists of a 5-bit ($D_{5-1}$) binary weighted DAC with a redundant LSB ($D_0$) and a bank of chopper switches (Fig. 9). It is controlled by an external trimming code ($D_{5-0}$). The DAC compensates the bridge offset by effectively adding a scaled and chopped version of $V_{bias}$ to the output of the bridge.

The total DAC capacitance should be kept small to minimize its impact on the CCIA’s noise gain [18]. With a 5-V bias, a ±100-mV bridge offset can be expected. To bring the
offset into the input range of the CCIA, two references, \(k_1 V_{\text{bias}}\) (1.25 V for \(D_{3–3}\)) and \(k_2 V_{\text{bias}}\) (0.625 V for \(D_{2–0}\)), are derived from \(V_{\text{bias}}\) by a resistive divider. In this way, the DAC capacitance is reduced from 1.6 to 0.87 pF, 11.4 \(\times\) smaller than \(C_{\text{in}}\), ensuring that the divider’s noise contribution is much less than the CCIA. The unity capacitances are 49.1 fF for \(D_{5–1}\) and 35.6 fF for \(D_0\) (the smallest in the process).

The resistive divider has a total resistance of 36 k\(\Omega\), and is made from polysilicon resistors, which can handle bridge bias voltages up to 6.6 V. The charger switches are protected by connecting the node \(P\) to an ESD-protected pad to ensure that the charger gates are not exposed to voltages above the supply (Fig. 6). The polarity of the compensating signal can be inverted via the choppers, so the CCIA’s output can be expressed as (be inverted via the choppers, so the CCIA’s output can be supplied (Fig. 6). The polarity of the compensating signal can be inverted via the choppers, so the CCIA’s output can be supplied (Fig. 6). The polarity of the compensating signal can be inverted via the choppers, so the CCIA’s output can be supplied (Fig. 6). The polarity of the compensating signal can be inverted via the choppers, so the CCIA’s output can be supplied (Fig. 6).

\[ H(s) = g_{\text{m2}} \left( R_{Z2} + \frac{1}{sC_{\text{int2}}} \right) \approx \frac{R_{Z2}}{R_s} + \frac{1}{s R_s C_{\text{int2}}} \]  

where \(g_{\text{m2}}\) is the transconductance of the OTA \(G_{\text{m}}\) shown in Fig. 10.

The jitter of the sampling clock will translate into input-referred noise, thus degrading the signal-to-noise ratio (SNR) of the CT\(\Delta \Sigma\)M. However, the jitter requirement is relaxed by the relatively narrow signal band. The SNR\(_{\text{dac}}\) determined by the sampling clock jitter \(\sigma_{\text{gate}}\) is given by [1]

\[ \text{SNR}_{\text{dac}} = 10 \cdot \log \left( \frac{1}{16 \cdot \text{OSR} \cdot f_b^2 \cdot \sigma_{\text{gate}}^2} \right) \]  

where over sampling ratio (OSR) is 1000, and \(f_b\) is 1 kHz. Assuming 10-ps (rms) jitter, SNR\(_{\text{dac}}\) is 118 dB, which is sufficient for bridge readout. In the worst case, 42-ps (rms) jitter would result in a noise level close to that of the ROIC. However, this noise power contribution, caused by clock jitter, to the pressure sensing system is less than 6%.

Similarly, the jitter of the gating clock \(\sigma_{\text{g}}\) in the 1st integrator also degrades the modulator’s in-band noise performance. SNR\(_{\text{igate}}\) determined by this jitter is given by [27]

\[ \text{SNR}_{\text{igate}} = 10 \cdot \log \left( \frac{1}{4 \cdot (V_{\text{IAO}}/V_{\text{ref}})^2 \cdot f_b \cdot f_{\text{gate}} \cdot \sigma_{\text{igate}}^2} \right) \]
where $V_{\text{IAO}}$ is the CCIA output signal, and $f_{\text{gate}}$ is 400 kHz. In the worst case, when $V_{\text{IAO}}$ is $\pm 1$ V, the resulted SNR$_{\text{igate}}$ with 10-ps (rms) jitter is 133 dB, 15 dB lower than the SNR$_{\text{jdac}}$.

### IV. Measurement Results

The ROIC was implemented in a 180-nm standard CMOS technology and has an active area of 0.73 mm$^2$ (Fig. 12). The core of the ROIC, including the CCIA, CT$\Delta$SM, CDAC$_1$, CDAC$_2$, and clock generator, consumes 1.2 mA from a 1.8-V supply. The on-chip resistive divider is supplied by the bridge bias voltage $V_{\text{bias}}$, which may be as high as 6.6 V.

The performance of the ROIC and that of the entire pressure sensing system have been characterized experimentally. The digital processing of the calibration has been done in MATLAB. The results will be described in Sections IV-A and IV-B.

#### A. Electrical Measurements

The fast Fourier transform (FFT) plots of the ROIC’s output bitstream, based on $2 \times 10^7$ samples, is shown in Fig. 13. It can be seen that the modulator’s 1st integrator must, indeed, be chopped to ensure that the ROIC’s noise spectrum becomes flat from 0.1 Hz to 2 kHz. The spectrum corresponds to a 3.7-nV/$\sqrt{\text{Hz}}$ noise level. By decimating the ROIC’s output with an off-chip sinc$^3$ filter and then acquiring $2 \times 10^8$ samples of the filter’s output over 100 s, its 1/$f$ corner frequency was found to be about 0.04 Hz.

#### B. System Measurements and Temperature Calibration

Measurements on 10 samples show that the ROIC achieves 0.3% relative gain error and 7-μV voltage offset (Fig. 14). Enabling CDAC$_2$ reliably boosts its input impedance by a factor of 5 (Fig. 14). The CMRR of the ROIC is shown in Fig. 15(a).

To test the effectiveness of the gating technique, a 118-mV signal with 2-kΩ source impedance was applied to the inputs of the ROIC when the resistive voltage divider was biased at 6 V. Gating the CT$\Delta$SM reduces the ROIC’s gain temperature drift from 74.6 to 8.9 ppm/°C, and reduces its offset temperature drift from 105 to 12.5 nV/°C. As shown in Fig. 15(b), gating the CT$\Delta$SM also improves the ROIC’s INL from 105 to 28 ppm.

The ROIC’s performance is summarized in Table II and compared with the state of the art. It achieves both high accuracy and energy efficiency for ±10-mV bridge signals, while accommodating up to 3.3-V input CM voltage. With a 3.7-nV/$\sqrt{\text{Hz}}$ input-referred noise PSD, it achieves an NEF (in [28]) of 5 and a power efficiency factor (PEF) (in [29]) of 44.

#### B. System Measurements and Temperature Calibration

The ROIC was combined with an AC4010 pressure sensor to realize a pressure sensing system. As shown in Fig. 16(b),
the water-level difference in a U-tube manometer was precisely controlled by a linear stage to create a well-defined differential pressure [30].

Moving the right leg of the U-tube manometer relative to the left one by ±10 mm with a 2.5-mm step, then results in ±100-Pa pressure change. The real-time response of the sensing system is shown in Fig. 17(a). The pressure sensing system has a pressure sensitivity of 0.0025 (1/Pa). To evaluate the system’s resolution, the inputs of the differential pressure sensor were shorted to avoid mechanical interference from the environment. The pressure resolution, obtained from the standard deviation of 5000 samples (decimated by sinc3 filter with a length of 1000), is found to be 10.1 mPa with a 0.5-ms conversion time for each decimated sample [Fig. 17(b)].

In practice, the temperature drift of a bridge sensor can be corrected by system calibration (Fig. 1). This usually involves exposing the bridge sensor to at least two well-defined temperature levels and measuring its output. The sensor’s drift can then be corrected if the ambient temperature is known.
e.g., by realizing a temperature sensor in the ROIC. However, the accuracy of this approach is limited by bridge self-heating, which can create temperature differences between the bridge and temperature sensor.

A more accurate approach is to use the bridge itself as a temperature sensor, by measuring its temperature-dependent resistance. To calibrate the bridge resistance over temperature, both the bridge sensor and the ROIC were placed in an oven-stabilized aluminum block next to a PT100 thermometer (Fig. 18). A reference resistor (100 Ω, ±3 ppm/°C [31]) was placed in series with the bridge as a shunt current sensor. The voltage across the reference resistor was read out by Keithley 2002. In this way, the bridge resistance, and thus, the temperature on the bridge can be measured.

The effectiveness of the resulting calibration was tested by measuring the bridge sensor’s offset drift over temperature. After a two-point calibration, the offset drift decreases from 244 μV over a 50 °C range, to about 3 μV [Fig. 19(a)].

To compare the results of both methods and the output of the bridge is measured by both the ROIC and a Keithley 2002 (Fig. 18). As shown in Fig. 19(b), the residual offset with monitoring the bridge resistance (red curves) is about 2× better than that obtained by monitoring the bridge temperature using PT100 thermometer (black curves). The residual errors obtained by the ROIC (solid curves) are in good agreement with that obtained by the Keithley 2002 (dashed curves).

V. Conclusion

An energy-efficient ROIC for a differential pressure sensing system has been presented. To maximize bridge sensitivity with high energy efficiency, the beyond-the-rails capability of a CCIA is exploited to allow the bridge biasing voltage to exceed the ROIC’s supply voltage. A bridge offset compensation is implemented in a ratio-metric manner, which is robust to variations in temperature and bridge biasing voltage. A dual positive feedback path scheme is used to boost the input impedance of the ROIC. A gated-input CTAΣM is proposed to digitize the amplified signal and avoid the error caused by the output spikes of the CCIA. Measurements show that the ROIC achieves both precision and energy efficiency with an NEF of 5, which represents the state of the art. The ROIC was tested together with a piezo-resistive differential pressure sensor. The experimental results show that the applied techniques are effective. The resulting pressure sensing system achieves 10.1-mPa (1σ) resolution with a 0.5-ms conversion time. The ROIC dissipates about 30% of the system’s power dissipation and contributes about 6% of its noise power. Moreover, a temperature calibration, to reduce the bridge temperature dependence, has shown a factor of 80× improvement on the system’s offset drift over a 50 °C range.

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References


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