A Highly Linear Sensor System Using SEIR for Distortion Evaluation of Sensor Front-end

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***Abstract*—This paper presents a highly linear sensor system by applying the stimulus error identification and removal (SEIR) method for distortion evaluation and calibration. The proposed distortion evaluation method estimates the true linearity of sensor front-end and analog-to-digital converter (ADC) that both are integrated as an analog front-end without separately measuring each block. The effectiveness of the proposed distortion evaluation and calibration technique was successfully demonstrated by a prototype illuminance sensor system.**

Keywords—sensor system, analog-to-digital converter (ADC), stimulus error identification and removal (SEIR), analog front-end (AFE), internet of things (IoT).

I. INTRODUCTION

In recent years, the needs of sensor analog front-ends (AFEs) are increasing due to the growth of the internet of things (IoT). The low power consumption and integrating AFE with digital circuits like digital signal processor (DSP) into one mixed-signal system-on-chip (SoC) is desired because the IoT applications require a long battery lifetime and small size.

Although the highly integrated system can bring a lot of benefits like small size, evaluation of each sub-blocks in such an integrated system become more difficult. For example, distortion evaluation. A typical sensor system is shown in Fig. 1. All needed blocks are integrated into a mixed-signal SoC. It is difficult to evaluate each block independently and the effects among each block under AFE. For example, the effect of the variable equivalent impedance of sensor front-end. Thus it is hard to obtain the true nonlinearity that can not be measured under single-block. On the other hand, a vast variety of sensor devices (transducers) are developed [1-3]. As shown in Fig.1, many sensor front-ends have a nonlinear characteristics between the input physical quantity and the output electrical signal. Therefore, some methods for evaluation and calibration of the nonlinearity of sensor front-end under AFE are strongly required.

The stimulus error identification and removal (SEIR) method [4] is a technique for obtaining the linearity of high precision ADC while using input test signals which is less linear than the ADC. Usually, in order to test the linearity of high precision ADC, a highly linear input test signal is necessary. The generation of such a highly linear test signal is very challenging and increases the test cost. The SEIR method releases the requirement of the input test signal while maintaining the accuracy of the evaluation.

Our proposed method makes it possible to estimate and calibrate the true nonlinearity of sensor front-end and ADC under AFE by applying the SEIR method. The proposed technique can be used for various kinds of sensor systems. In this paper, an prototype illuminance sensor system with a Cadmium sulfide (CdS) photoresistor was chosen to demonstrate the effectiveness of the proposed technique.

The characteristics of sensor devices change easily due to process-voltage-temperature (PVT) variation. Using the information of the estimated true nonlinearity, it is possible to obtain more accurate and stable data of the sensed signal.

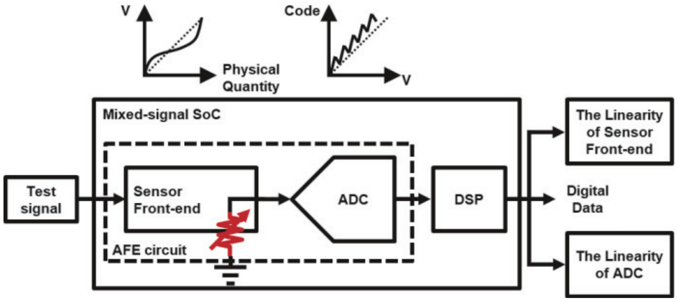

Fig. 1. A typical sensor system and distortion

The rest paper is organized as follows. In Section II, the distortion characteristics of the illuminance sensor front-end used in our system are analyzed, and the power consumption of different architecture also mentioned. Section III describes the proposed method and the developed low power illuminance sensor system for demonstrating the proposed method. Section IV is the experimental results and Section V is the conclusion of this paper.

II. DISTORTION CHARACTERISTICS OF SENSOR FRONT-END

The sensor front-end usually combines the sensor device with the readout circuit. The common readout circuit of the illuminance sensor device and its transfer curve are shown in Fig. 2 (a). It uses a transimpedance amplifier (TIA). Although the transfer curve of this circuit is well linear, it usually consumes more power and has worse SNR because an amplifier is required.

The other type of readout circuit and its transfer curve are shown in Fig.2 (b), in which a CdS photoresistor is used for sensor devices and is what we use as the sensor front-end in our system. This type uses simple voltage divider and thus has low power consumption. Also, from the viewpoint of noise characteristics, compared to TIA, this type has good SNR. However, the transfer curve of this circuit is intrinsically nonlinear.

Using our proposed method, once the true nonlinearity of sensor front-end and ADC can be estimated, the data is used for calibration and a highly linear sensor system with low power consumption but nonlinear sensor front-end can be realized (Fig. 2 Proposed).

The above is summarized in Table I. our proposed sensor system achieved low power consumption, high SNR, and well linear.

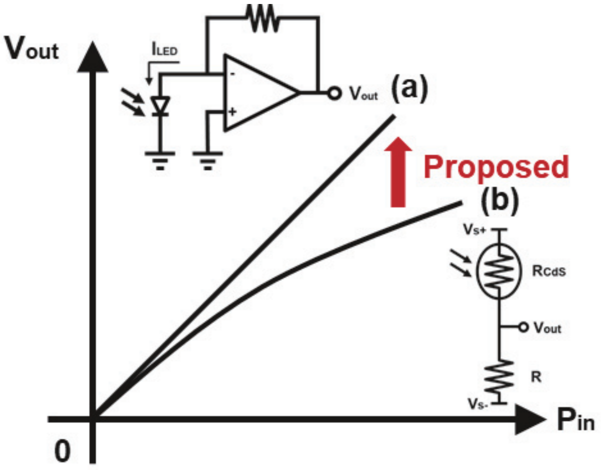

Fig. 2. The transfer curve of different sensor front-end

TABLE I. COMPARASION OF SENSOR FRONT-END OF ILLUMINANCE SENSORS

Architecture	TIA (a)	Voltage Divider (b)	**Proposed (c)**
Power	☹	☺	**☺**
SNR	☹	☺	**☺**
Linearity	☺	☹	**☺**

III. PROPOSED LOW POWER ILLUMINANCE SENSOR SYSTEM AND DISTORTION EVALUATION AND CALIBRATION METHOD

In this section, we first introduce our low power illuminance sensor system and then explain the proposed evaluation and calibration method for the true linearity of the sensor system. The effect of source impedance on the integral nonlinearity (INL) of ADC is also mentioned.

A. Low Power Illuminance Sensor System

The low power illuminance sensor system is shown in Fig. 3. The sensor front-end using a CdS photoresistor (Senba GL5549) as shown in Fig. 2 (b) is combined with a 12-bit differential ADC (Texas Instruments ADS7044).

The test signal for the illuminance sensor is generated by an LED emitting white light. The SEIR method uses a less linear ramp signal for test input. In our sensor system, for obtaining the true nonlinearity of sensor front-end purely, our proposed method uses a linear ramp signal for the test signal on purpose. To modulate the light intensity of the LED as a linear ramp waveform, the bias current of LED (I_{LED}) is swept as ramp waveform but with calibration. The nonlinearity between the light intensity and bias current is measured and calibrated independently by using a power detector.

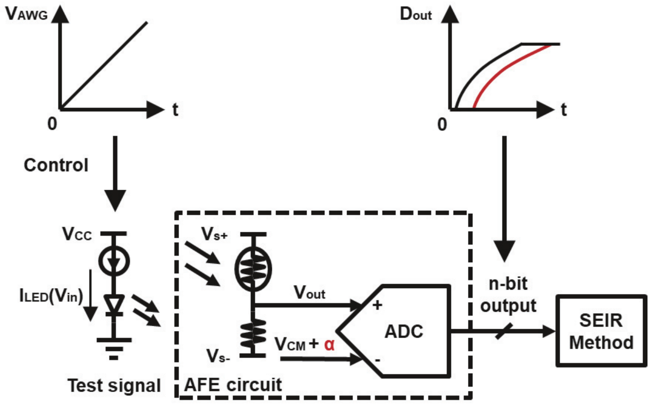

Fig. 3. Proposed low power illuminance sensor system

Because the output of the sensor front-end is single-ended, one of the input terminals of differential ADC is connected to common mode voltage V_{CM}. Note that by doing so, the resolution of ADC is reduced by 1-bit. In this experiment, the resolution of the ADC becomes 11-bit. The definition of LSB is $1\ LSB = V_{DD}/2^{11}$, where V_{DD} is the supply voltage of ADC.

B. Review of SEIR Method

The static characteristics of ADC that is monotonic and has no missing code are the same for the identical input signals. The SEIR method uses two identical nonlinear input test signals (typically ramp waveform) except a fixed offset to estimate the nonlinearity of ADC based on the reproducibility of the static characteristics of ADC. According to [4], the INL of kth digital code of ADC can be expressed in the transition time form as

$$INL_k = (N-2)t_k + \sum_{j=1}^{M} a_j F_j(t_k) - k, k = 1, 2, \ldots, N-3 \quad (1)$$

where N is the resolution of ADC, t_k is the transition time of kth digital code, M is the order of nonlinear basis function $F_j(t)$, and a_j is the coefficient of $F_j(t)$.

The fixed offset α results in a time difference in the output digital code of ADC. Thus we have two INLs using Eq. (1).

$$INL_{k,1} = (N-2)t_{k,1} + \sum_{j=1}^{M} a_j F_j(t_{k,1}) - k \quad (2)$$

$$INL_{k,2} = (N-2)t_{k,2} + \sum_{j=1}^{M} a_j F_j(t_{k,2}) - k - \alpha \quad (3)$$

The static characteristics of ADC are the same, we obtain

$$(N-2)(t_{k,2} - t_{k,1}) = \sum_{j=1}^{M} a_j \left(F_j(t_{k,1}) - F_j(t_{k,2})\right) + \alpha \quad (4)$$

From the known time difference, the SEIR method uses some nonlinear basis functions such as sine waves to approximate the nonlinearity term of test signal expressed in the form of time. By using the LS method, we can obtain the coefficient a_j. Thus, the nonlinearity of the input test signal and ADC can be separated and estimated.

C. Proposed Nonlinearty Evaluation Method

In this study, we aim to estimate the true nonlinearity of the sensor front-end and ADC without separately and independently measuring them. The true nonlinearity is hard to be measured under single-block using a conventional method. Although the SEIR method is for testing ADC, our proposed method uses the same concept to obtain true nonlinearity. For this purpose, the offset should be added at the input of ADC to make time difference. There are two choices to add the offset. One is to add the offset to the power supply of sensor front-end, and the other is to add the offset to the common-mode voltage V_{CM} of ADC. As shown in Fig. 3, we add the offset α to the V_{CM} of ADC. If the offset is added to the power supply of the sensor front-end, it will be affected easily due to PVT variation and thus is not always a fixed offset for ADC. On the other hand, V_{CM} is intrinsically a DC voltage, and a fixed offset can be easily added by adjusting the DC voltage. Furthermore, it is easy to extend the proposed method to the variety of sensor systems, which means our proposed method is in universal use.

From the two output digital codes of ADC with and without fixed offset, the true nonlinearity of sensor front-end and ADC can be separated and estimated respectively without knowing them independently in advance. The true nonlinearity of ADC can be estimated as in Eq. (2) or Eq. (3). The second term of Eq. (1) stands for the nonlinearity of the input signal of ADC. In our case, based on the definition of LSB of ADC used, it is multiplied by -1 and is the nonlinearity of sensor front-end expressed in Eq. (5).

$$INL_{k,sensor} = -\sum_{j=1}^{M} a_j F_j(t_k)\,, k = 1, 2, \ldots, N-3 \qquad (5)$$

Therefore, the proposed method can obtain true nonlinearity of the sensor front-end and ADC at once and is simple.

D. Effect of Sourse Impedance on the INL of ADC

The INL of ADC are strongly affected by source impedance (output impedance) of the circuit which is connected to the ADC as shown in Fig. 4.

To confirm how much the equivalent source resistance (R_{source}) affects the INL of ADC, R_{source} expressed in Eq. (6) as a model of the equivalent resistance of Fig. 2 (b) is changed and the corresponding INL of ADC can be evaluated.

$$R_{source} = \frac{R \times R_{CdS}}{R + R_{CdS}} \qquad (6)$$

E. Linearity Calibration

The linear characteristics between the input physical quantity and output digital code are desired for the use of data, but the output of AFE is nonlinear due to the distortion of devices and each circuit block.

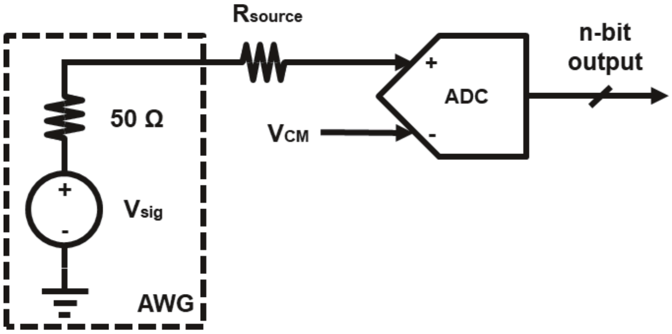

Fig. 4. Effect of the sourse impedances on differential ADC

By definition of the INL of ADC, we can calibrate the nonlinearity by using the equation expressed as

$$D_k = \left(D_{out,k} + INL_k\right) \qquad (7)$$

where INL_k is the INL of kth digital code of ADC, $D_{out,k}$ is the kth real digital code, and D_k is the kth calibrated digital code.

IV. EXPERIMENT RESULTS

In this section, the experimental results are shown. Fig. 5 shows the experimental illuminance sensor system. Linearity separation of sensor front-end and ADC is discussed. And linearity calibration of the sensor system is demonstrated. The clarity of the input-output characteristics of the sensor system is also mentioned.

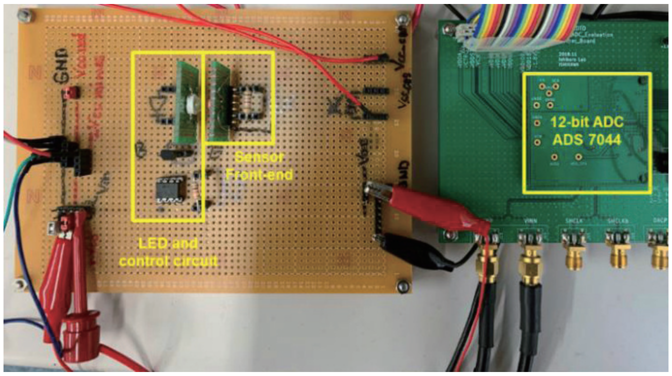

Fig. 5. The experimental illuminance sensor system

A. Nonlinearity of LED

This study aims to estimate and calibrate the true and pure nonlinearity of a sensor front-end. The nonlinearity of the test signal is not a concern. Therefore, as mentioned before, the highly linear light source is required for test signal generation. It is known that the characteristics between the bias current and light intensity of LED is relatively linear. However, it is not enough linear in this experiment. Therefore, the nonlinearity of the LED is, at first, evaluated by using a power detector (ADVANTEST ADCE8230E) and calibrated by using an inverse function of the characteristics. Fig. 6 shows the measured characteristics and result of the linearity error with and without calibration. The power stands for the light intensity and is the interval of the test signal. The calibrated error is 0.55%, which is 1/7 of the one without calibration.

B. Nonlinearity of Proposed illuminance Sensor Front-End

The measured characteristics between the input sensed signal expressed as I_{LED} and the output voltage V_{out} of the sensor front-end is shown in Fig. 7. It is apparent that the sensor front-end has nonlinear characteristics. Generally, a nonlinear sensor front-end is not easy to use because it may not maintain the same accuracy in the interval of the sensed signal. That means it may not reflect the sensed value accurately. Aiming for the low power, our proposed system uses the nonlinear sensor front-end on purpose. Therefore, linear calibration is necessary for our system.

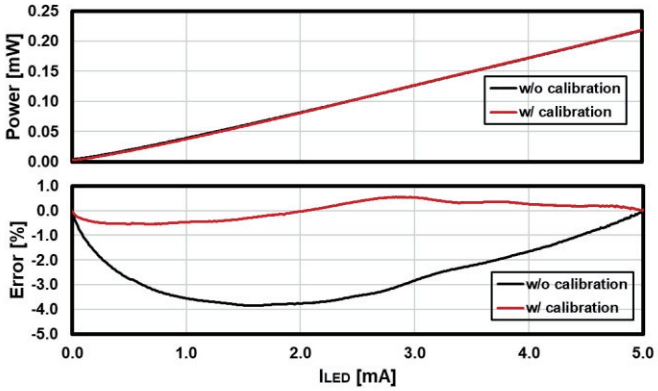

Fig. 6. The characteristics and error of LED

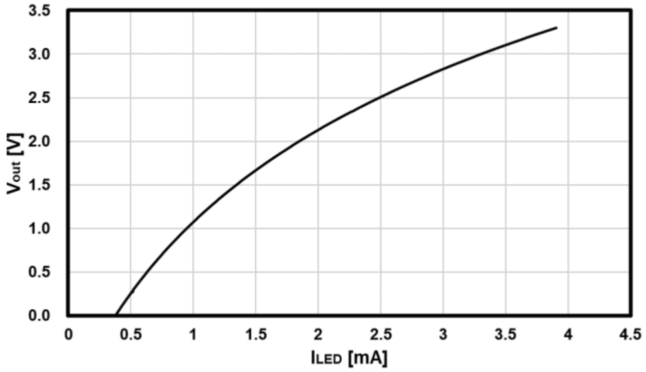

Fig. 7. The transfer curve of sensor front-end

C. Result of Linearity Separation

As explained previously, the source (output) impedance of the circuit connected to the ADC affects the INL of ADC. Fig. 8 shows the measured results of 1.8 kΩ and 51.6 Ω. The 1.8 kΩ corresponds to the one output impedance of the sensor front-end. The 51.6 Ω corresponds to the situation that arbitrary waveform generator (AWG) is directly connected to the ADC which is a common situation ADC performance evaluation. It is apparent that the INL of ADC is strongly affected by the source impedance.

Fig. 9 shows the estimated INL of ADC and sensor front-end using the proposed method. For comparison, the independently measured INLs are also plotted.

The independently measured INL of ADC is obtained by testing ADC itself using the conventional histogram method [5]. Note that the left side of the INL shows more difference than the right side. That is because the independently measured INL is tested under the condition that the source resistance does not change using an AWG, which means the conventional testing. While the estimated INL is tested under the condition that the source resistance changes with the change of light, which means testing without separating each block. This shows that it is impossible to obtain the true INL by testing separately. Thus, using the proposed method we could obtain the true INL of ADC in the sensor system which is hard to estimate independently.

The independently measured INL of sensor front-end obtained by testing the sensor front-end itself and calculating the INL by mapping the voltage into the digital code based on the ADC in the sensor system. Both the estimated and individually measured INL show the same nonlinearity.

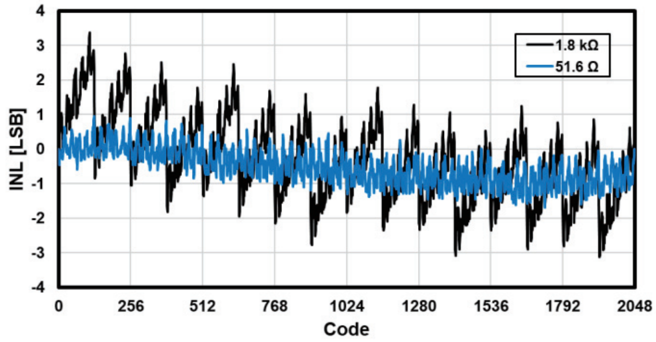

Fig. 8. The INL of ADC affected by the source resistance

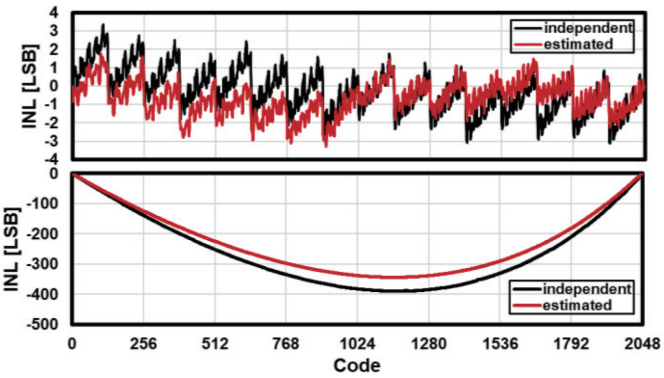

Fig. 9. The seperated linearity of ADC and sensor front-end

As shown in this figure, our proposed method estimated the true nonlinearity successfully even if the system is integrated like an SoC and is not allowed to test each-block independently. Also, the true nonlinearity contains the effects only under AFE.

D. Linear Calibration of illuminance Sensor System

The characteristics of sensor front-end change significantly due to PVT variation. Therefore, the input-output characteristics of the sensor system are not stable, and thus it is hard to use. However, our proposed technique makes it possible to calibrate a sensor system even it is affected due to PVT variation and makes the input-output characteristics stable and makes a sensor system easy to use.

Based on the estimated true INLs containing all effects (e.g. PVT variation), the linearity of the output digital code of ADC can be calibrated using Eq. (7). As shown in Fig. 10, the characteristics between the input bias current of LED (I_{LED}) which corresponds to the sensed light intensity and the output digital code of ADC is nonlinear without calibration. However, the linear characteristics is successfully obtained after calibration, which means the sensor system is always stable and accurate.

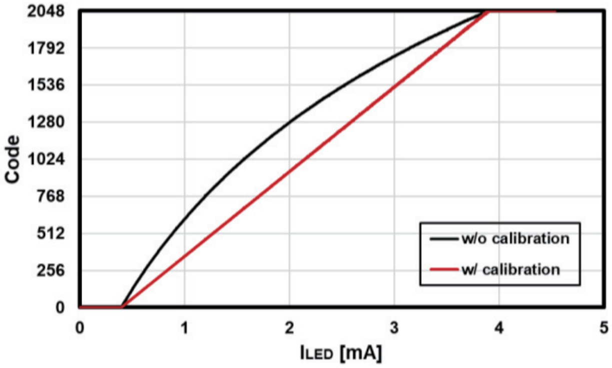

Fig. 10. The characteristics of proposed sensor system

V. CONCLUSION

This paper proposed a distortion evaluation method that can easily obtain the true nonlinearity of sensor front-end and ADC under AFE at once. From the experimental results, our proposed method was verified using the experimental illuminance sensor system. The linearity was improved by calibration using the true nonlinearity. Our proposed method also makes it possible to choose low power consumption but nonlinear sensor front-ends. Therefore, it is easier to realize a highly linear and low power consumption sensor system.

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