Ultra Low-Distortion, Low-Noise Transimpedance Amplifier

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Abstract—A transimpedance amplifier for use with a proposed ultra-linear current-output DAC was designed, implemented, and experimentally verified. The target precision was a signal-to-noise-and-distortion ratio (SINAD) of 122 dBFS, or 20 effective number of bits (ENOB), over a bandwidth of 100 kHz. Experimental verification was limited by the available measurement instrumentation, but the target was met.

Index Terms—Measurement, measurement techniques, precision measurements, operational amplifiers, low-noise amplifiers, current measurement.

I. Introduction

Several integrated CMOS devices present a current-based output signal, such as photo-detectors and digital-to-analog converters (DACs). These devices do not behave as ideal current sources. To minimize distortion, they should ideally be connected to zero ohm at ground, or a fixed, potential [1].

The best off-the-shelf DACs can yield approximately 16 ENOB at audio frequencies (20 Hz to 20 kHz) [2]. The Authors are working to improve this performance to more than 18 ENOB from DC to 100 kHz. The most promising DAC topologies produce a current output, and to reliably measure the performance of these experimental DACs, a low-noise, low-distortion output stage is required that at the same time is able to uphold the output impedance and voltage requirements; hence a transimpedance amplifier (TIA) [1] is required. This also enables it to interface most standard instrumentation, typically requiring a voltage signal. The proposed TIA enables 20 ENOB with a 100 kHz bandwidth, whilst providing ideal output conditions for the DAC.

II. Transimpedance Amplifier

Fig. 1 shows a TIA configuration using an operational amplifier (opamp), complete with typical noise sources [3]. The gain of the amplifier is $A = -R_f$, and the value of R_f is set according to the magnitude of the signal current and the desired output voltage of the application.

The feedback capacitor C_f limits the bandwidth of the feedback network. Limiting the bandwidth mitigates stability issues and reduces high-frequency noise. The cut-off frequency is given by $f_c = 1/2\pi R_f C_f$.

The current noise of the opamp itself, i_{OAn}, contributes directly as an input noise current. The input capacitance C_{in} is the capacitance at the input node of the opamp, typically consisting of parasitic capacitances. C_{in} causes the input voltage noise e_n of the opamp to generate an input current noise [3]. As a noise density it is expressed as $i_{nc} = e_n C_{in} \omega = e_n C_{in} 2\pi f$; increasing proportionally with frequency.

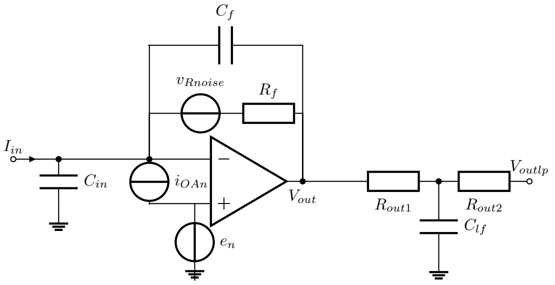

Fig. 1. Bandwidth-limited transimpedance amplifier with noise sources and impedance-matching low-pass filter on the output

The feedback resistor R_f also generates current noise i_{Rnoise} consisting of Johnson noise and excess noise [4]:

$$i_{Rnoise} = \sqrt{4k_B T/R_f} + i_{excess}$$

Here k_B is Boltzmanns constant and T is temperature; i_{excess} is excess noise. This is also known as $1/f$-noise and depends on the technology used to manufacture the resistor and the current flowing through it [4].

The output impedance of the TIA is the same as the output impedance of the opamp, which is ideally $R_{out,opamp} = 0\,\Omega$. To match the impedance with a $50\,\Omega$ cable, a passive RC filter is added on the output with $R_{out1} + R_{out2} + R_{out,opamp} = 50\,\Omega$. By adding C_{lf} and choosing $R_{out1} \gg R_{out2}$, the greatest portion of the Johnson noise becomes band-limited. Note that both R_{out} resistors will contribute excess noise (not shown in Fig. 1), but this it is negligible compared to the excess noise of R_f since it is not amplified.

III. Design

The amplifier is designed for an input current of 20 mA peak-to-peak, and an output voltage of 5 V peak-to-peak (7.07 Vrms). Hence the gain is $R_f = 5\,\mathrm{V}/20\,\mathrm{mA} = 250\,\Omega$.

To achieve a bandwidth of 100 kHz, a feedback loop cut-off frequency of 200 kHz was chosen combined with a low-pass filter frequency of 100 kHz. Hence $C_f = 1/2\pi R_f f_c \approx 3.2\,\mathrm{nF}$. The input capacitance C_{in} is estimated to be 7 pF, based on the chosen connectors and the PCB layout.

The opamp OPA1612 from Texas Instruments was selected for its low noise and low distortion. It has $e_n = 1.1\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and $i_{OAn} = 1.7\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$ at 1 kHz.

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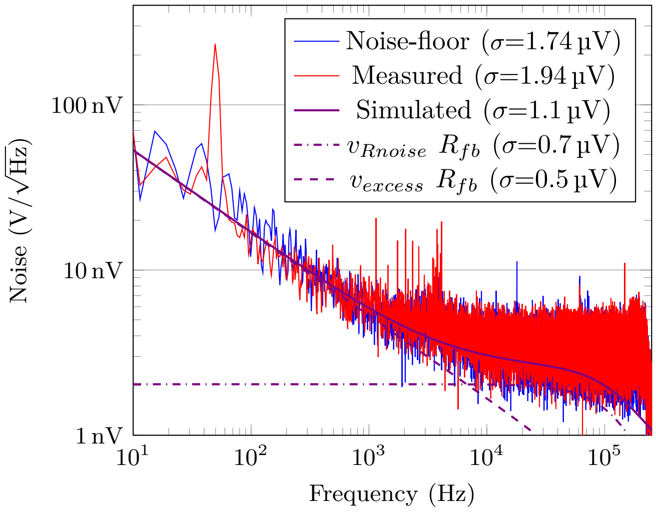

Fig. 2. Output noise

Given the above, the noise terms i_{OAn} and i_{nc} become insignificant compared to the noise from the feedback resistor $i_R noise$.

IV. Results

SPICE simulations of the TIA were performed, using the manufacturer provided opamp model and a worst-case noise-index of -30 dB for the excess noise of R_f. The opamp is the dominant source of harmonic distortion, but this is unfortunately not modeled in the provided SPICE models. An approximate value of -128 dB can however be derived from the datasheet.

The prototype TIA was measured with a National Instruments PXI-5922 oscilloscope, using a sampling frequency of 500 kHz in order to achieve maximum resolution and the lowest possible noise floor for the instrument. The noise-floor was measured by connecting directly to the output of the TIA with the input of the TIA shorted to signal ground. To measure harmonic distortion, a SWG03 precision Waveform Generator by the Czech Metrology Institute was connected through a 44 Ω precision resistor to generate an input current for the TIA. The resulting output voltage was measured with the oscilloscope.

Fig. 2 shows the simulated and measured noise of the TIA, as well as the noise floor of the oscilloscope. The standard deviation σ for the entire 10 Hz to 250 kHz bandwidth is given for each series. Fig. 3 shows both the output spectrum of the TIA and the waveform generator connected directly to the PXI-5922 oscilloscope.

V. Discussion

Noise simulations in Fig. 2 show that the excess noise of the feedback resistor dominate at lower frequencies, up to around 1 kHz. Between that frequency and the cut-off at 100 kHz, the Johnson noise of the feedback resistor is dominating.

Elevated noise levels at 50 Hz and some spikes in the 10 kHz to 40 kHz are observed, likely due to the power supply. These may be eliminated by using better supply decoupling and/or a differential configuration.

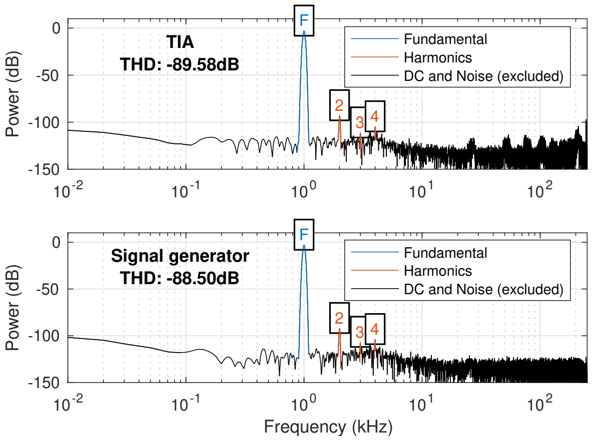

Fig. 3. Measured harmonic distortion

The instrument noise floor is too high to accurately measure the noise performance of the TIA. At lower frequencies, the TIA may perform better than the simulations due to the worst-case assumption of the Noise Index. At high-frequencies, the instrument noise floor is significantly higher than in the simulations; as this effect was not included.

Total harmonic distortion (THD) measurements in Fig. 3 likely do not reflect the performance of the TIA, but rather that of the signal generator. The minor difference in THD as well as the noise shape at higher frequencies may be explained by the effect of loading the signal generator with the shunt resistor.

VI. Conclusion and Outlook

The experimental results show that the TIA has equal or lower amounts of noise and distortion than the measurement setup. The signal-to-noise-and-distortion (SINAD) ratio of the TIA with the measured noise floor and THD of -128 dBFS from the opamp datasheet is then

$$20\log\left(7.07\,\text{V}/(1.94\,\mu\text{V}+2.83\,\mu\text{V})\right) \approx -123\ \text{dBFS}$$

indicating that the TIA is exceeding our target of 20 ENOB.

An improved measurement setup must be devised in order to measure these extremely low levels of noise and distortion.

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