Application Report
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Thermal Noise Analysis in ECG Applications

Jack Li
High-Performance Analog

ABSTRACT

This article discusses the thermal noise source of electrocardiogram (ECG) applications based on the ADS1298 and ADS1298R family of multichannel, simultaneous sampling, 24-bit, delta-sigma (ΔΣ) analog-to-digital converters (ADCs). This report offers several observations on identifying the major sources of thermal noise in an ECG system, and recommends a method to improve thermal noise performance.

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1 Introduction

The Association for the Advancement of Medical Instrumentation (AAMI) specifications allow 30-μV_{PP} noise at 150-Hz bandwidth during a 10-second recording. The primary sources of thermal noise in an ECG system are generally caused by either resistors or amplifiers. This stochastic noise is specified as *root-mean-square (RMS) noise*, and is proportional to the square root of the noise bandwidth.

Considering that the bulk of the system noise is Gaussian in nature, computed as RMS but specified by AAMI as peak-to-peak, we must develop a scale factor that gives us a confidence level that the peak-to-peak noise will not exceed 30 μV in any 10-second recording (5000 samples at 500 Hz). That level of confidence (1 part in 5000) equates to approximately 8σ. RMS is, by definition, 1σ, so we must have an RMS noise level approximately 1/8 the AAMI peak-to-peak specification, or 3.75-μV_{RMS}.

2 Noise in ECG Signal Path

There are three components of the system noise. Each source is analyzed a bit differently. Figure 1 illustrates the ECG signal path based on the ADS1298/98R.

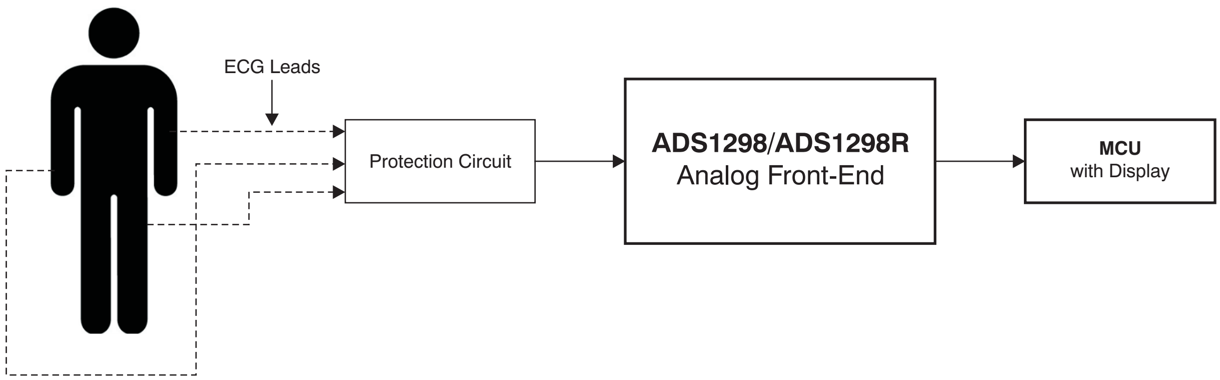

Figure 1. ECG Signal Path Based on ADS1298/98R

The primary noise sources are the 10-kΩ defibrillation protection resistors embedded in the patient block.

2.1 AAMI Signal Source (51 kΩ||47 nF)

The AAMI specification calls for a source impedance of 51 kΩ in parallel with 47 nF. For more information, refer to the skin electrode contact model in Figure 1 as well as Figure 59 in the ADS1298/98R product data sheet. Figure 2 shows the block diagram of the ADS1298/98R analog front-end circuit.

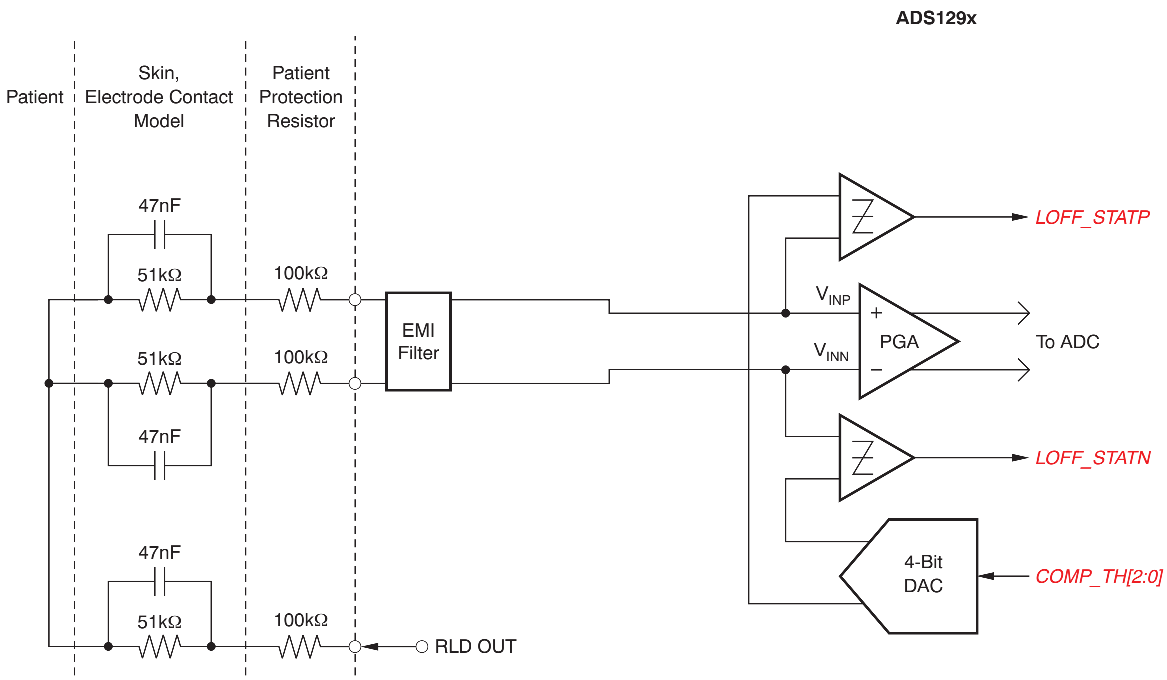

Figure 2. Analog Front-End Input Circuit

Thermal noise is produced by a random motion of charges. The RMS open-circuit voltage (*e*) across a resistor (*R*) is given by Equation 1.

$$e^2 = 4kTR\Delta f \quad (1)$$

where:

- k is temperature (Kelvins)
- R is resistance (Ω)
- Δf is frequency (Hz)
- k is Boltzmann's constant (1.38^{-23} joule/Kelvins)
- e is voltage (V_{RMS})

Example 1. Noise in RC Network

As an example of noise source determination, calculate the noise in a RC network. Figure 3 shows a typical RC network.

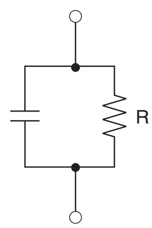

Figure 3. Calculating Noise in an RC Network

The parallel RC network impedance (*Z*) is given by Equation 2:

$$Z = R \,||\, \left(\frac{1}{j\omega C}\right) = \frac{R}{1 + j\omega RC} = \frac{R}{1 + (\omega RC)^2} - j\frac{\omega R^2 C}{1 + (\omega RC)^2} \quad (2)$$

Given that ω = 2πf, the total open-circuit noise voltage is shown in Equation 3:

$$\overline{v_t^2} = \int_0^\infty 4kTRe(Z)df = \int_0^\infty \frac{4kTR}{1 + (2\pi fRC)^2} df$$

$$= \frac{2kT}{\pi C}\int_0^\infty \frac{dx}{1 + x^2} = \frac{2kT}{\pi C}[\tan^{-1}x]_0^\infty = \frac{kT}{C} \quad (3)$$

Note that *R* has dropped out of Equation 3, so e^2 is independent of R. At room temperature, the thermal noise of a 47-nF capacitor is approximately 295.8 nV_{RMS} (with T = 298 Kelvins, or approximately +25 ºC). This noise source occurs twice: once on the measured input and again on the reference (R_A). The noise voltage across a capacitor depends only upon temperature and capacitance. The RMS sum of two such sources is approximately 418.32 nV_{RMS}.

2.2 Thermal Noise from Protection Resistor

There are 22-kΩ and 10-kΩ current limiting resistors from the electrode to the input of the ADS1298. Here, we calculate the thermal noise for all components in the ECG signal path. Figure 4 illustrates the protection architecture of a defibrillator, for example.

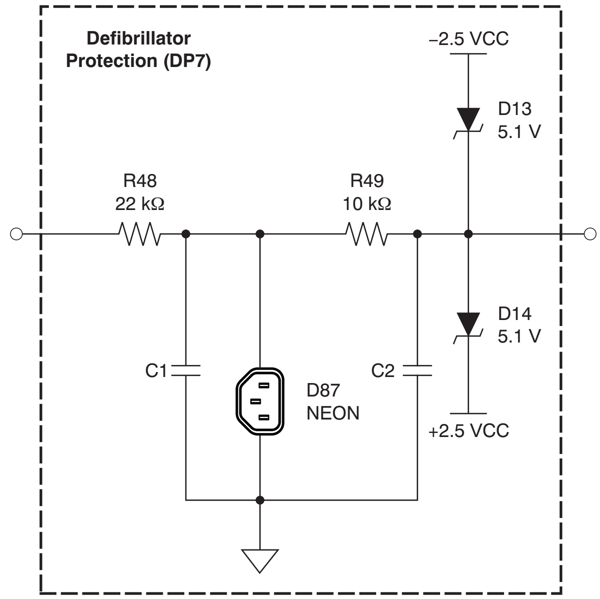

Figure 4. Defibrillation Protection Part

The noise units are nV/√Hz. Using Equation 1 we obtain the following data:

- 32-kΩ input resistance (R_A): (4 nV/√Hz/ kΩ at +25°C) = 22.94 nV/√Hz

The protection circuit (R48, C1, R49, and C2) is also used as a second-order low-pass filter for anti-aliasing and radio frequency interference (RFI). Furthermore, the patient protection resistor value is limited by the maximum current under the fault conditions specified by AAMI/IEC.

2.3 ADS1298/98R Noise

Based on the information provided in the ADS1298/98R product data sheet, the noise measurement is taken with an internal reference, which includes the internal reference output noise. If we use a low-noise external reference, such as the REF5025, we can achieve better noise performance with a low gain setting. (The 2.5-V reference of the REF5025 output noise is 7.5 μV_{PP} at 0.1 Hz to 10 Hz; higher frequency noise is filtered by the reference output capacitor.) A minimum of 1000 consecutive readings are then used to calculate the RMS and peak-to-peak noise for each reading.

Table 1. ADS1298/ADS1298R Input-Referred Noise ($\mu V_{RMS}/\mu V_{PP}$) in High-Resolution Mode 3-V Analog Supply and 2.4-V Reference[(1)]

DR Bits of CONFIG1 Register	Output Data Rate (SPS)	–3dB Bandwidth (Hz)	PGA Gain = 1	PGA Gain = 2	PGA Gain = 3	PGA Gain = 4	PGA Gain = 6	PGA Gain = 8	PGA Gain = 12
000	32000	8398	335/3553	168/1701	112/1100	85/823	58/529	42.5/378	28.6/248
001	16000	4193	56/613	28/295	18.8/188	14.3/143	9.7/94	7.4/69	5.2/44.3
010	8000	2096	12.4/111	6.5/54	4.5/37.9	3.5/29.7	2.6/21.7	2.2/17.8	1.8/13.8
011	4000	1048	6.1/44.8	3.2/23.3	2.4/17.1	1.9/14.0	1.5/11.1	1.3/9.7	1.2/8.5
100	2000	524	4.1/27.8	2.2/15.4	1.6/11.0	1.3/9.1	1.1/7.3	1.0/6.5	0.9/6.0
101	1000	262	2.9/19.0	1.6/10.1	1.2/7.5	1.0/6.2	0.8/5.0	0.7/4.6	0.6/4.1
110	500	131	2.1/12.5	1.1/6.8	0.9/5.1	0.7/4.3	0.6/3.5	0.5/3.1	0.5/2.9

(1) At least 1000 consecutive readings were used to calculate the RMS and peak-to-peak noise values in this table.

We can see that the RTI noise of the ADS1298/98R is specified as 1.1 μV_{RMS} when the PGA gain = 6 and the data rate is 2 kSPS. For simple calculation, presuming that the internal filter is a single-pole filter, the noise bandwidth is π/2 times the –3-dB bandwidth; in this case, that value is approximately 822.68 Hz.

Now, we combine the noise from the AAMI source noise, the protection resistors, and the ADS1298/98R:

AAMI source noise: 418.32 nV_{RMS}

Protection resistors: 0.93 μV_{RMS} ($= 22.94 nV/\sqrt{Hz} \times \sqrt{822.68\ Hz} \times \sqrt{2}$)

RTI noise of ADS1298/98R: 1.1 μV_{RMS}

Total noise: 1.5 μV_{RMS}

Using our 8× conversion factor from RMS to peak-to-peak (explained in Section 1), this total noise is then 12 μV_{PP}, which is much less than the 30 μV_{PP}.

3 Summary

We can see from this report that we can optimize the protection resistor and reduce the noise bandwidth to achieve better noise performance. The noise factors discussed here only concern the thermal noise of the system, and do not include quantization noise or non-thermal sources (such as digital crosstalk, power-supply noise, and so forth). For electrosurgical interference (ESI), which is not addressed in this report, see Ref 5.

4 References

1. ANSI/AAMI EC11:1991/®2001, Diagnostic Electrocardiographic Devices.
2. Chinese Standard: YY 1079-2008, Electrocardiographic Monitors.
3. Markandey, V. (2009, revised 2010). ECG Implementation on the TMS320VC5505 DSP Medical Development Kit (MDK). Application report. Literature number SPRAB36B.
4. ADS1298 Product data sheet. Literature number SBAS459G.
5. Yelderman, M., Widrow, B., Cioffi, J., Hesler, E., and Leddy, J.E. (1983). ECG enhancement by adaptive cancellation of electrosurgical interference. IEEE Transactions on Biomedical Engineering, Vol. BME-30, No. 7, July 1983.

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