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Analog and Digital Gain in Microphone Preamplifier Design

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ABSTRACT

This paper examines the overall system noise performance of a microphone preamplifier system and the impact of providing some of the gain in both the analog and digital domains. Whereas some applications require up to 70 dB of system gain to bring microphone levels up to drive an A/D converter, the designer can elect to provide part of the gain in an analog stage and the remaining necessary gain in the DSP following the converter. As newer high-performance A/D converters realize dynamic range and THD specs greater than 100 dB, the use of digital gain post conversion becomes feasible. The noise impact of this approach is investigated and compared to others. Models are presented for the various noise sources in the system including source resistance, amplifier equivalent input noise, converter noise, and how they contribute to the total output noise of the system.

1 Introduction

We first analyze the microphone/preamp/ADC system dynamic range performance for the case of an ideal preamp and show how the system noise varies as a function of gain due to source noise and converter noise alone, setting the baseline noise to be expected. Next, we examine the conventional case where a single real world analog amplifier provides all of the gain and show its effect on output noise and contrast this with the ideal case. We also consider a system where two analog amplifiers in cascade provide all of the gain, where the effect of both amplifiers' EIN (equivalent input noise) as a function of system contribute to the total noise. Finally, a case where the system gain is split between an analog amplifier and digital gain in a DSP is considered. We shall see that for system gains above 10 dB, the two methods have nearly identical noise performance. In this paper all noise quantities are in a 20 Hz to 20 kHz bandwidth.

2 System Noise and Preamp Architecture

Figure 1 shows a block diagram for a mic Preamp driving an A/D converter in a typical application.

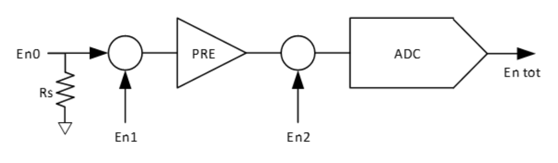

Figure 1. Noise sources in a preamp / ADC circuit.

E_{n0} is the thermal noise due to the source resistance and, in this example for a 150 ohm resistor, is -131 dBu. E_{n1} is the equivalent input noise of the preamp chip itself. Note that both noise sources are amplified by the gain of the PRE. E_{n2} is the noise floor of the ADC and is -112 dBu for a 120 dB dynamic range converter with a maximum input level of +8 dBu. The overall noise at output of the ADC is the root sum of squares of these three contributions.

Figure 2 shows the noise contributions as a function of system gain using a noiseless preamp so that we can see the effects of both the source and the converter. As the gain increases, the ADC noise (yellow) remains constant at -112 dBu since it is after the preamp gain.

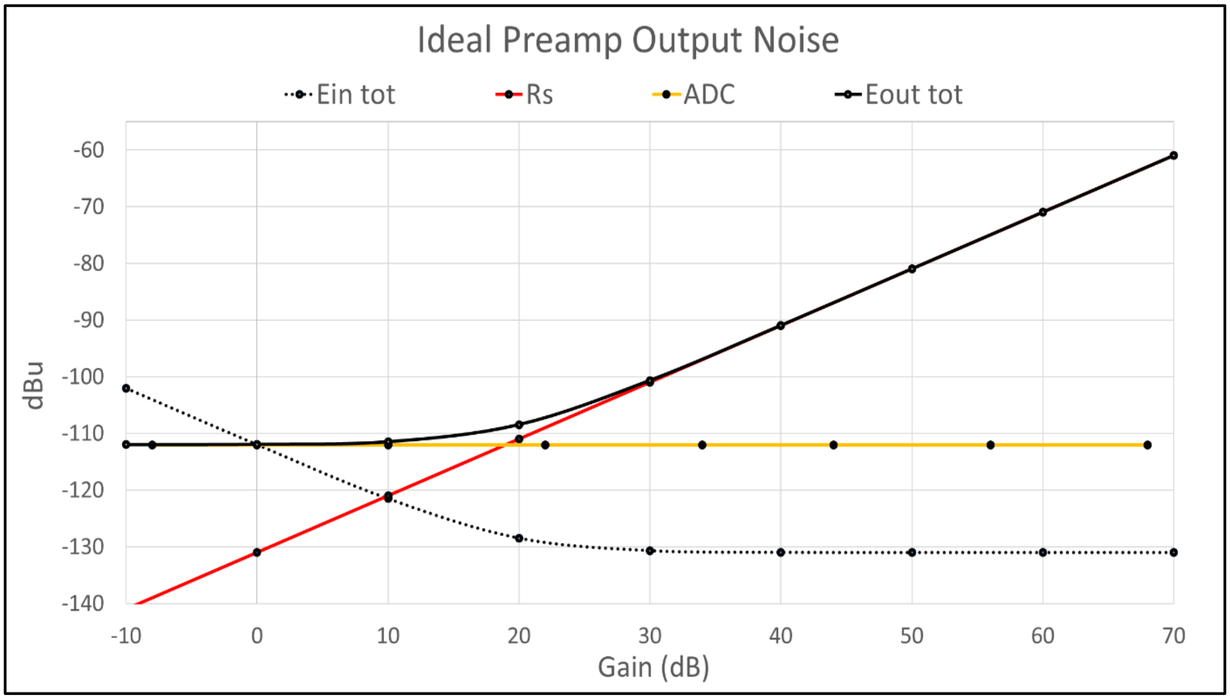

Figure 2. Noise sources in an ideal preamp.

The source resistance noise (red) increases linearly with preamp gain and ranges from -131 dBu at 0 dB gain to -61 dBu at 70 dB of gain. $E_{out\text{-}tot}$ (black) is the resultant total noise at the output due to all contributions. Note that for gains below +20 dB, E_{out} is determined by the ADC noise, while for gains above +30 dB, source noise dominates. $E_{in\text{-}tot}$ (black dash) is the equivalent input noise, the $E_{out\text{-}tot}$ referenced back to the preamp input. This example shows the best case for low noise since it has been used an ideal, noiseless preamp. Real preamps will contribute more noise to $E_{out\text{-}tot}$.

3 System Noise for 34 dB-gain and 70 dB-gain preamp ICs

Figures 3 and 4 show the noise contributions for 34 dB gain (THAT6261) and 70 dB gain (THAT1580) preamp ICs, respectively. The individual contribution from each source is shown, as well as the total noise output and E_{in}, all as a function of gain. The yellow curve is the ADC noise floor and it is not affected by the changing gain. The red line is the source contribution to total noise and is amplified by the preamp gain. The green and blue lines are the preamp output noise contributions.

4 Cascaded 68 dB Analog Gain

To increase the preamp gain beyond its 34 dB maximum, the two channels can be cascaded and provide nearly 70 dB of gain. This is shown in the Figure 5 block diagram and includes the noise sources for each preamp section (E_{n1}, E_{n2}).

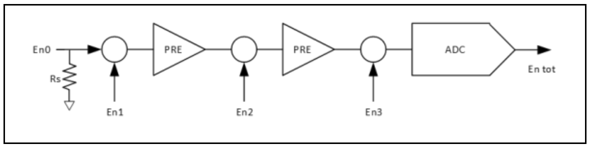

Figure 5. Cascaded 68 dB analog gain.

Figure 6 shows the noise contributions to the total output noise ($E_{out\text{-}tot}$) due to each source. The 68 dB of total gain is distributed between the two channels of the preamp IC. The first 34 dB of system gain is provided by the first stage, while the second stage remains at 0 dB gain. Then, the first stage holds at 34 dB gain and the second stage ramps up to 34 dB providing system gain from 34 dB to 68 dB. The first stage noise (green) is identical to that for a single preamp case, as shown in Figure 3, up to a gain of 34 dB and then rises linearly with system gain as stage 2 gain increases from 0 dB to 34 dB. The second stage noise contribution (blue) contributes very little to the total noise for gains above 34 dB.

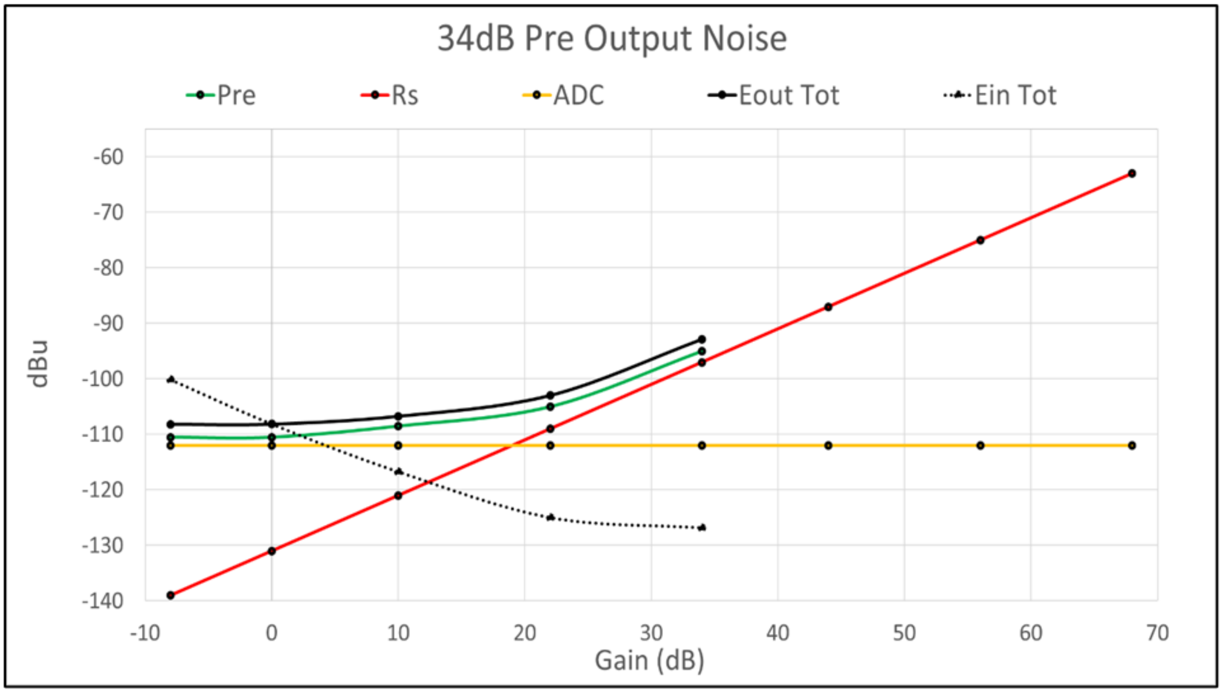

Figure 3. Noise sources in a 34 dB gain preamp.

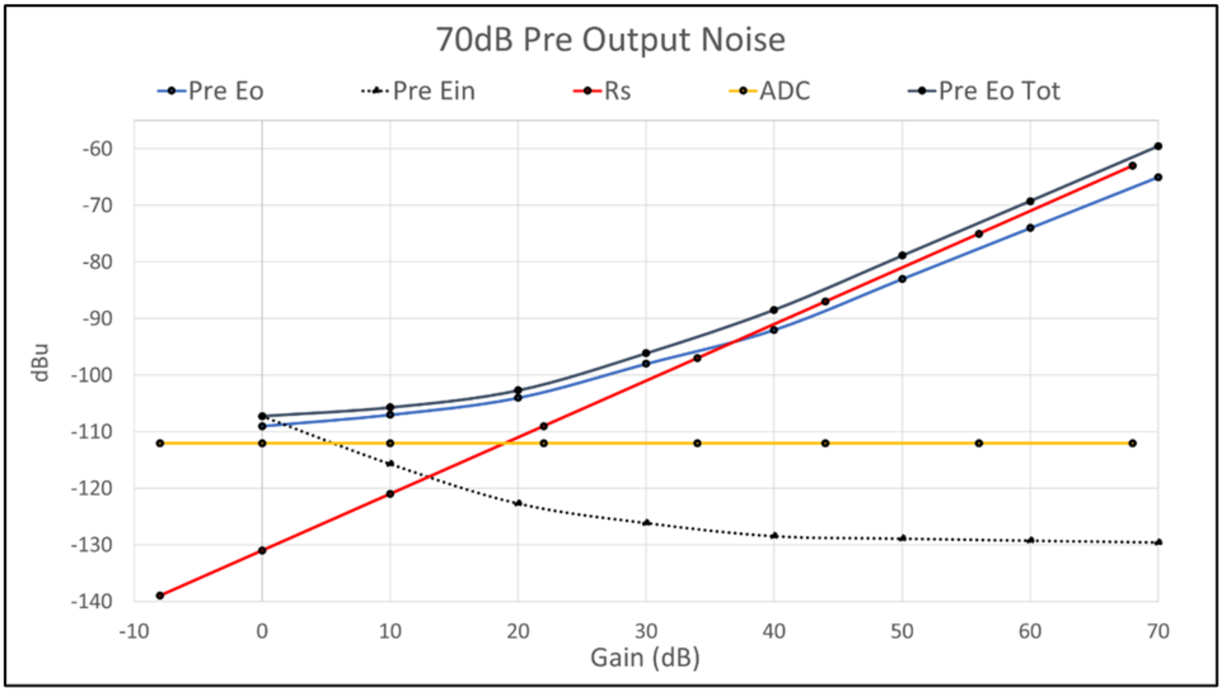

Figure 4. Noise sources in a 70 dB gain preamp.

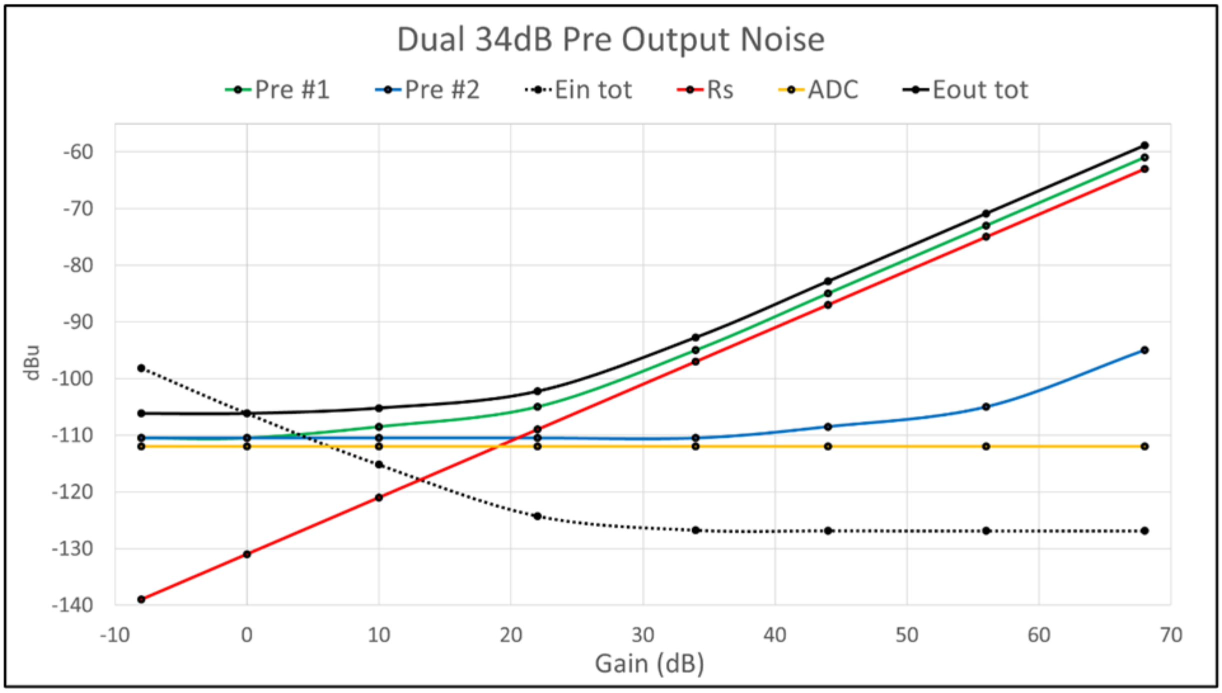

Figure 6. Cascaded two 34 dB gain preamps for 68 dB analog gain.

5 Digital Gain

Another approach to add 34 dB of gain is to use the DSP following the ADC as shown in Figure 7. The DSP can range through the 34 dB of gain with arbitrary dB-steps as desired. Note that the DSP gain also amplifies the ADC noise contribution, but it is not much of an addition to the overall noise since it is 15 dB below the contributions from the preamps and the source resistance.

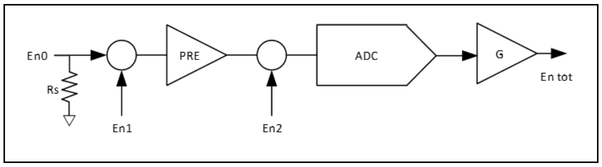

Figure 7. Preamp with analog and digital gains.

Figure 8 shows the noise contributions to the total output noise due to each source. As in the previous case, the analog preamp provides the first 34 dB of gain while the DSP holds at a gain of 0 dB. For the remaining 34 dB to 68 dB of system gain, the analog preamp holds at 34 dB of gain while the DSP ramps from 0 dB to 34 dB gain. Note that the ADC noise contribution (yellow) is constant for gains up to 34 dB and is then amplified by the DSP gain as it ranges from 0 dB to 34 dB. Fortunately, this ADC noise is far below the Rs source noise or the analog preamp noise.

6 Compare Analog and Digital Gain

The difference between the analog cascaded 70 dB gain case (Figures 5 + 6) and the analog plus digital gain case (Figures 7 + 8) is clearly minimal. The total noise for analog gain (green) differs from the total noise for the analog plus digital gain (blue) by ~1 dB and only for system gain <20 dB. This is due to the extra contribution of the second preamp stage when the first preamp stage is at low gain. Above 20 dB gain they perform equally. The total E_{in} noise is shown by the dotted lines for each gain case (Figure 9.)

7 ADC THD+N

Another consideration when using digital gain is that ADC distortion may also be amplified. For most delta-sigma converters, the THD+N spectrum is dominated by converter noise as shown in Figure 10. This is due to the inherent linearity of the 1-bit quantizer at the heart of the delta-sigma converter. The THD curve in Figure 11 also shows this, where for each increase of input signal by 20 dB, the THD drops by a factor of 10. This implies that for signals from -90 dBFS to -10 dBFS the harmonics are below the noise floor. For the last 10dB of signal level, the harmonics rise out of the noise floor and the THD curve levels out.

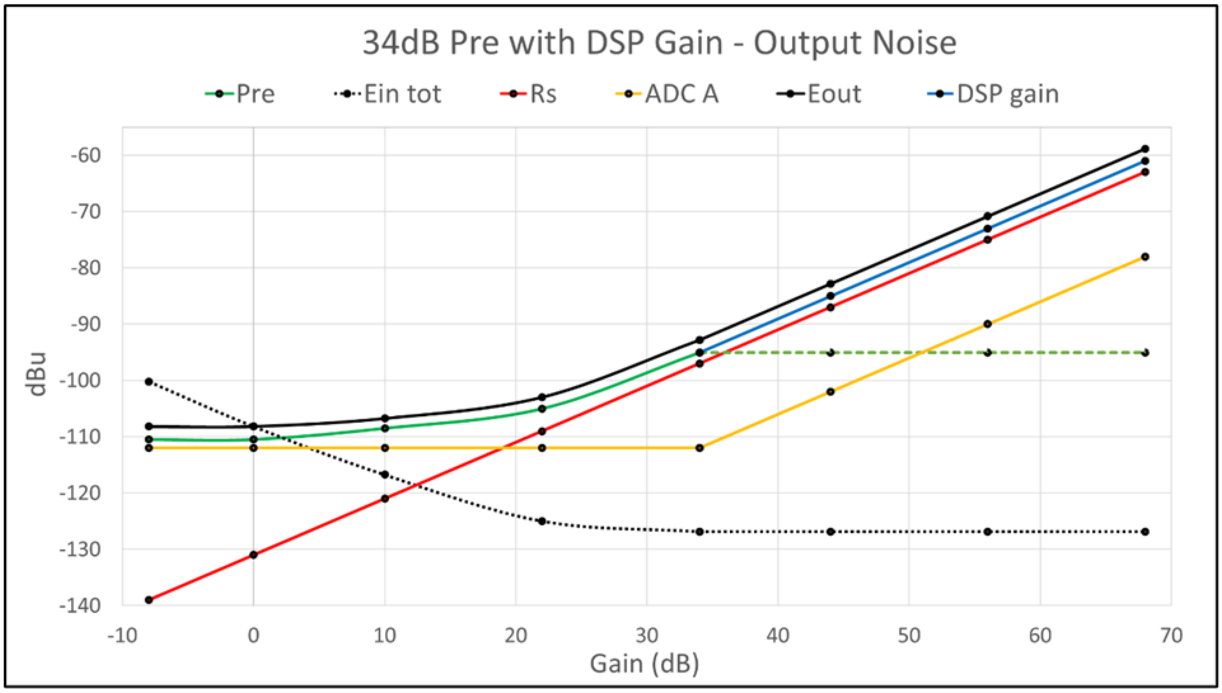

Figure 8. Pre with external 34 dB digital gain.

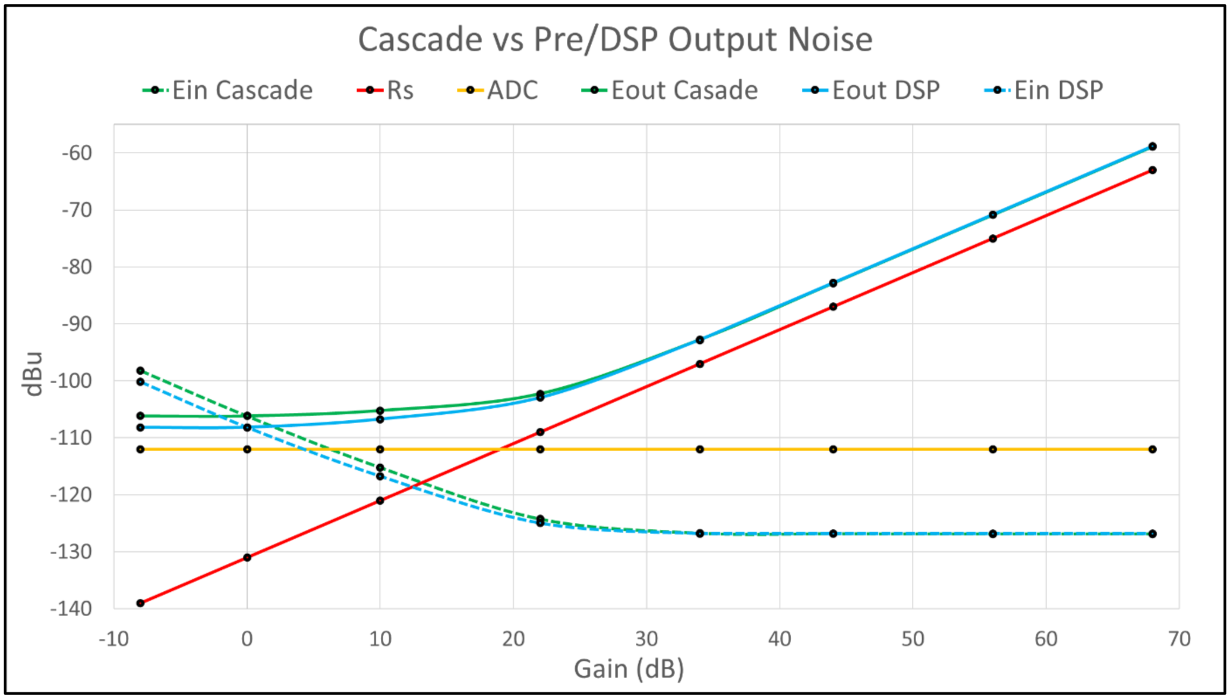

Figure 9. Comparison of Analog and DSP gain methods.

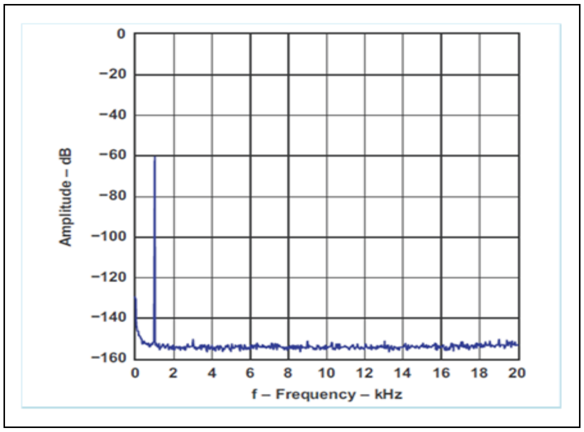

Figure 10. Typical ADC spectrum for -60 dBFS input.

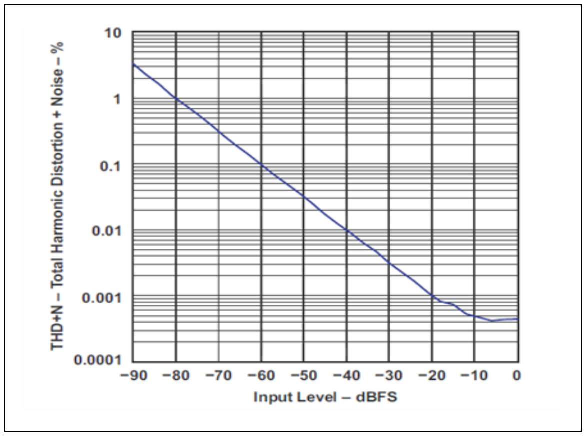

Figure 11. Typical ADC THD vs. input level.

8 Conclusion

Adding more gain to a balanced preamplifier design can be accomplished by either adding another analog gain stage or by a DSP multiply with equal resulting system noise performance. This investigation shows good results for implementing the first 34 dB of gain in the analog domain. The actual analog gain needed is also a function of the ADC noise floor as can be seen in the graphs.

9 Appendix A – Measured results

This section compares noise performance between calculated and measured results for the cascaded two-preamp case. The measurements were made with an Audio Precision AP-525 on a demo board for a two-channel programable preamp IC with up to 34 dB of gain. As in the earlier discussion of the two-preamp cascade noise, the calculated total E_{out} is shown in yellow. The actual AP measurements are shown on the cyan curve and agree quite well to the calculated one as shown in Figure 12.

The differences between the two are attributable to the fact that noise specs of a device are necessarily averages over a sample of production units. This shows a very good agreement of observed and calculated performance.

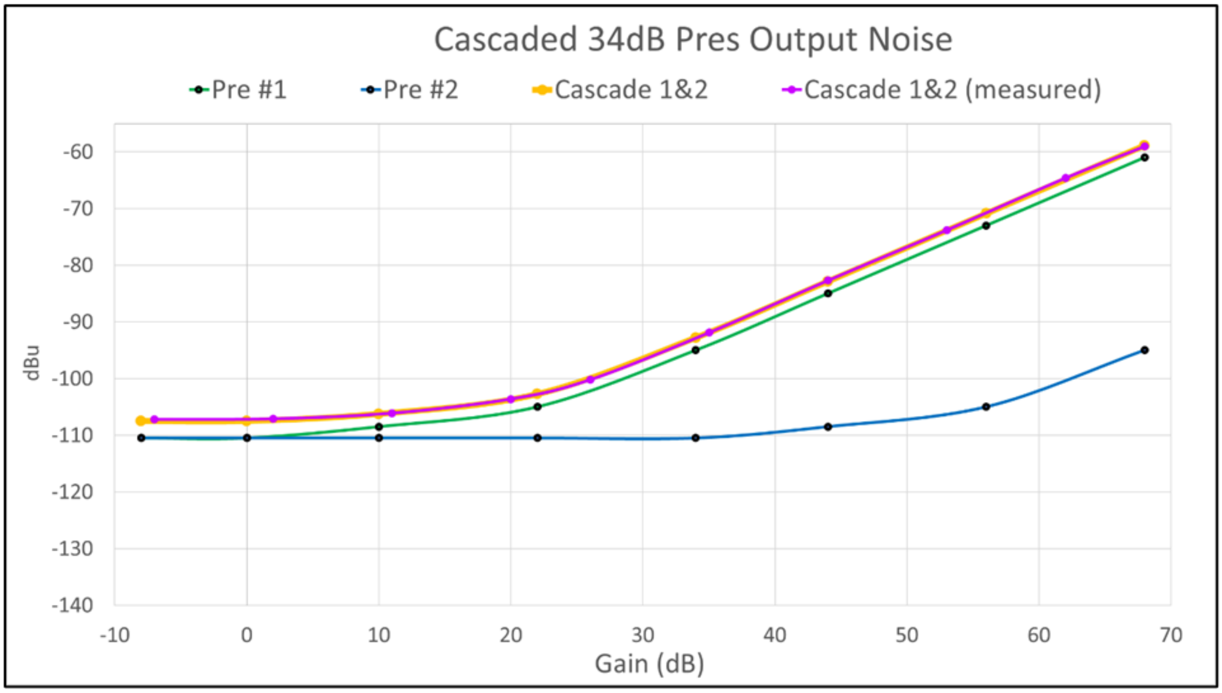

Figure 12. Comparison between calculated and measured cascaded preamps performances.

10 Appendix B – Sum of Noise Contributions

This section presents the calculations that are the basis for this investigation of gain considering the dual preamp cascade model as in Figure 13.

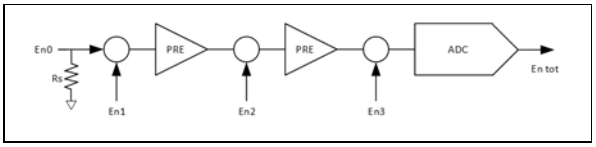

Figure 13. Cascaded 68 dB analog gain.

The four sources of noise, E_{n0} thru E_{n3}, all contribute to the total output noise as shown in Figure 14 and the equations that follow.

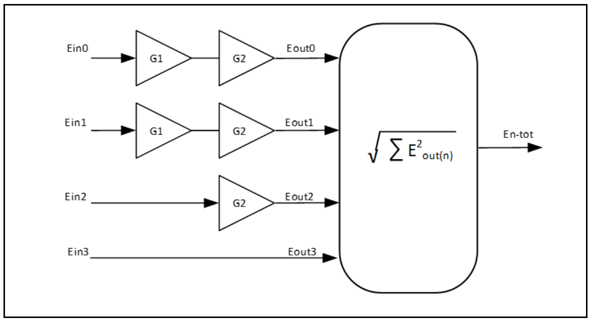

Figure 14. Sum of individual noise contributions.

The noise contributions (in V_{rms}) are:

Source R noise;

$E_{in0} = \sqrt{4kTBR}$ (1)

$E_{out0} = E_{in0} \cdot \mathrm{G1} \cdot \mathrm{G2}$ (2)

Pre #1 noise source;

$E_{in1} = E_{op1}$ (3)

$E_{out1} = E_{in1} \cdot \mathrm{G2} \cdot \mathrm{G2}$ (4)

Pre #2 noise source;

$E_{in2} = E_{op2}$ (5)

$E_{out2} = E_{in2} \cdot \mathrm{G1}$ (6)

ADC noise source;

$E_{in3} = E_{in\_ADC}$ (7)

$E_{out3} = E_{in\_ADC}$ (8)

Where T is temperature in degrees Kelvin, k is Boltzmann's constant (1.38E-23), B is bandwidth, and G1 and G2 are the stage gains. E_{op1}, E_{op2}, and E_{in_adc} are equivalent input noise values from the respective data sheets.

The resultant total output noise is a root, sum of squares of inputs calculation:

$$E_{out} = \sqrt{{E_{in0}}^2 + {E_{in1}}^2 + {E_{in2}}^2 + {E_{in3}}^2} \qquad (9)$$

11 Appendix C – Balanced preamp Noise Calculation

A typical balanced differential preamp is shown in Figure 15, followed by the equivalent input noise calculations used in this paper.

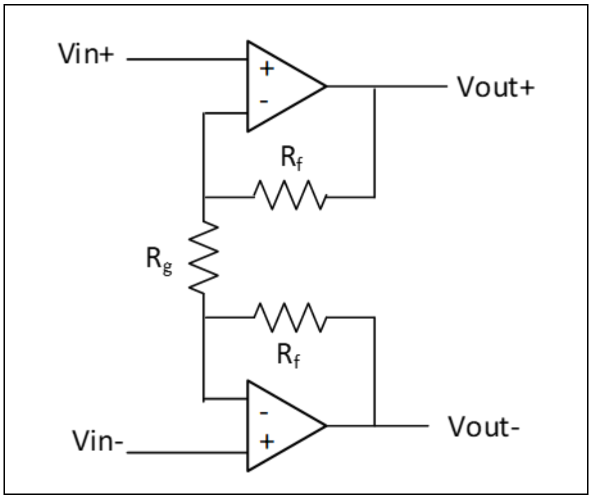

Figure 15. Balanced Diffamp.

Amplifier gain is given by

$Av = 1 + R_f/(R_g/2)$ (10)

To calculate equivalent input noise power Ein^2

Let $R_1 = R_f || (R_g/2)$ (11)

Then

$${E_{in}}^2 = 2[{E_{op}}^2 + {E_{R1}}^2 + (I_{op} \cdot R_1)^2] \qquad (12)$$

Where

${E_{R1}}^2 = 4kTB\ R_1$ (13)

${E_{op}}^2 = {E_{oa}}^2\ B$ (14)

${I_{op}}^2 = {I_{oa}}^2\ B$ (15)

Where E_{oa} and I_{oa} are the opamp's voltage noise and current noise specs in V/$\sqrt{Hz}$ or A/$\sqrt{Hz}$, respectively.

Finally, we plot E_{in} and even my dog believes:

$$E_{in} = \sqrt{{E_{in}}^2}$$

12 Acknowledgements

The authors would like to thank Gary Hebert, Jenny Luo, Fred Floru, and Ken Nevard, of THAT Corporation, for their contributions to, and review of this paper.

13 References

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