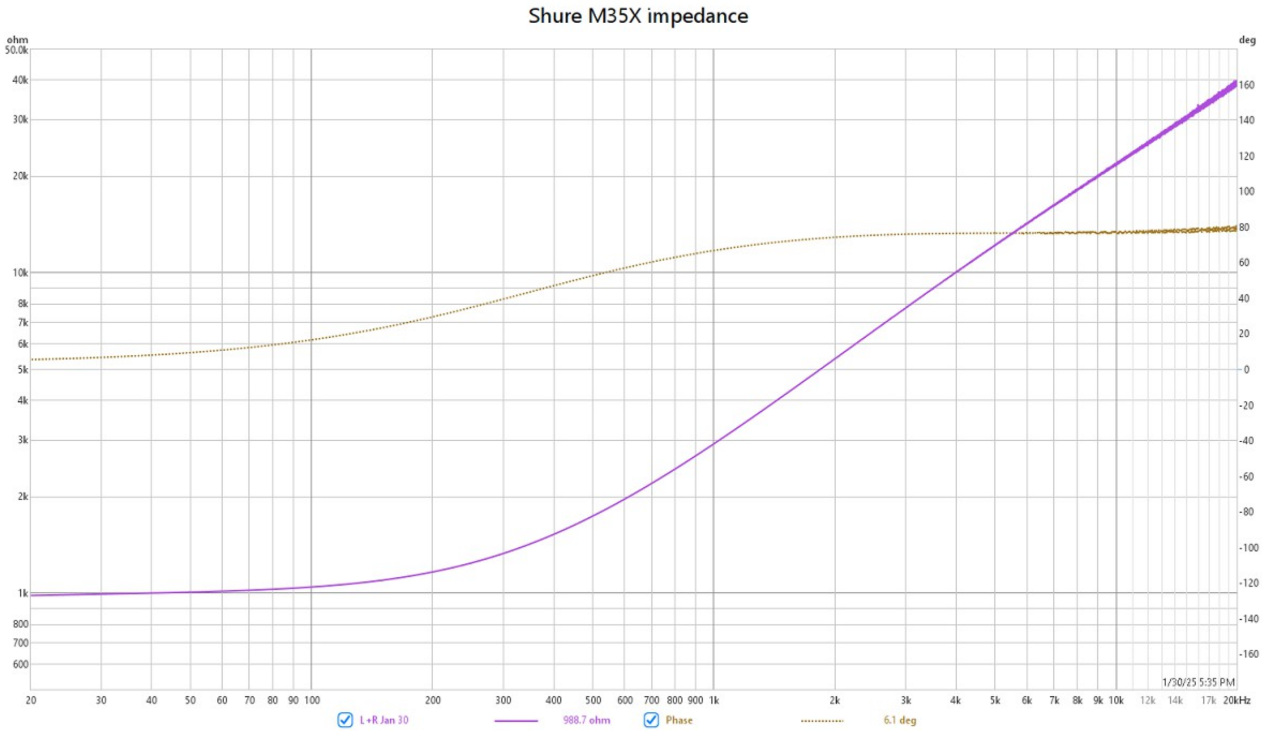
Measuring noise and SINAD of phono preamps properly

1. Intro

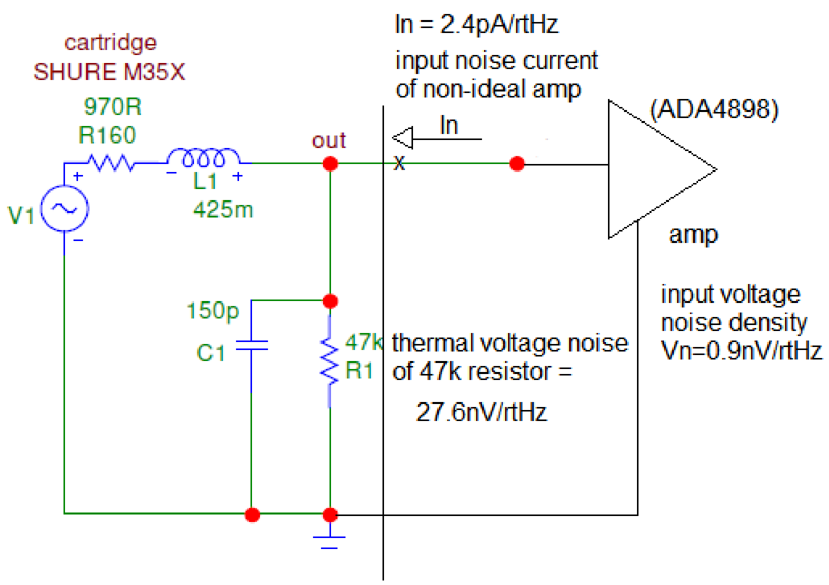
It is a temptation to measure phono preamplifiers the same way as if it was a common link stage preamp, to drive it from very low generator impedance and to measure the preamp output voltage. Similar way as when measuring with AP that has output impedance of 20 ohms. It is fast and simple. But, unfortunately, such measuring method may strongly deviate from results that we get with real life MM phono cartridges, speaking about noise and thus related SINAD. Below I will try to explain why measuring from low generator impedance may be misleading and may bring incorrect results and false priority when comparing phono preamplifiers.

2. MM cartridge dummy circuit and noise sources

I shall be simulating and testing with Shure M35X MM cartridge. Below you may see real world measurement of impedance of this cartridge from 20Hz to 20kHz:

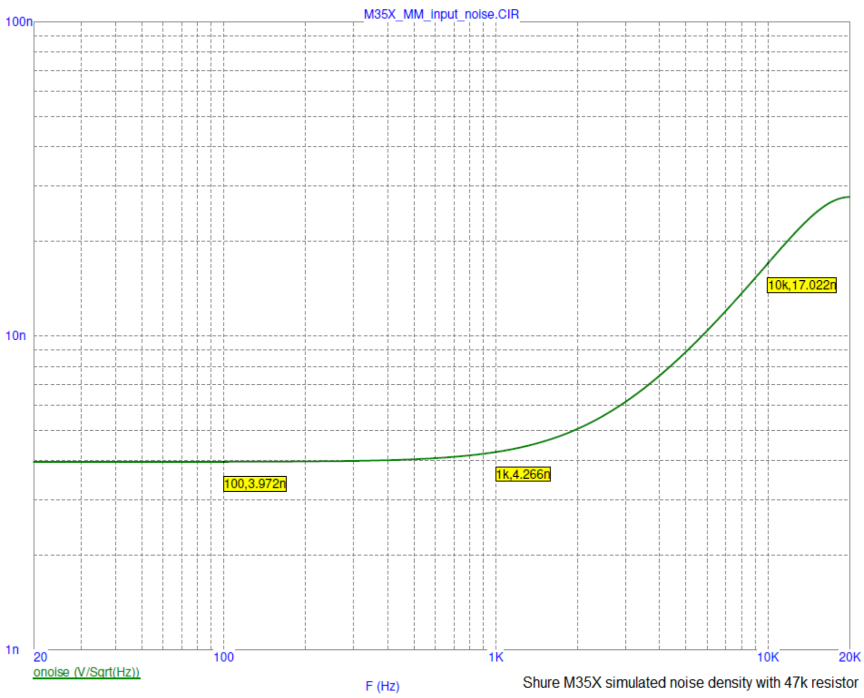


MM cartridge simplified model can be considered as a series connection of coil winding resistance and inductance. We shall see later that such simplification still gives very close results of simulation and real world measurements. Dummy circuit of Shure M35X MM cartridge is shown below, including the amplifier. We shall first investigate only the part of the image on the left side from the black border line, without contribution of the non-ideal amplifier.



The cartridge is represented with the 970 ohm resistor (R160) and 425 mH inductor (L1). R1 = 47 kohm represents the recommended load resistor and C1 = 150pF is a load capacitance, may that be a cable capacitance. Contribution of the non-ideal amp is not discussed yet.

Let's investigate noise voltage density at “out” node. This can be easily simulated and looks like this:



Shure M35X simulated noise density with 47k resistor

Up to 500Hz we can see the thermal noise contribution of the 970 ohm resistor, which would make 3.96nV/rt(Hz). This effectively shunts the thermal noise of 47k load resistor up to 500Hz. Above 500Hz, the contribution from rising impedance of the L1 inductance can be seen. At 10kHz, the noise voltage density at “out” node is 17nV/rt(Hz) and is still rising, until it reaches the thermal noise of the 47k load resistor, that is 27.6nV/rt(Hz). These are the limit values with an ideal amplifier and at the amplifier output they would be multiplied by amplifier gain at frequency of interest.

3. Contribution from the non-ideal amplifier

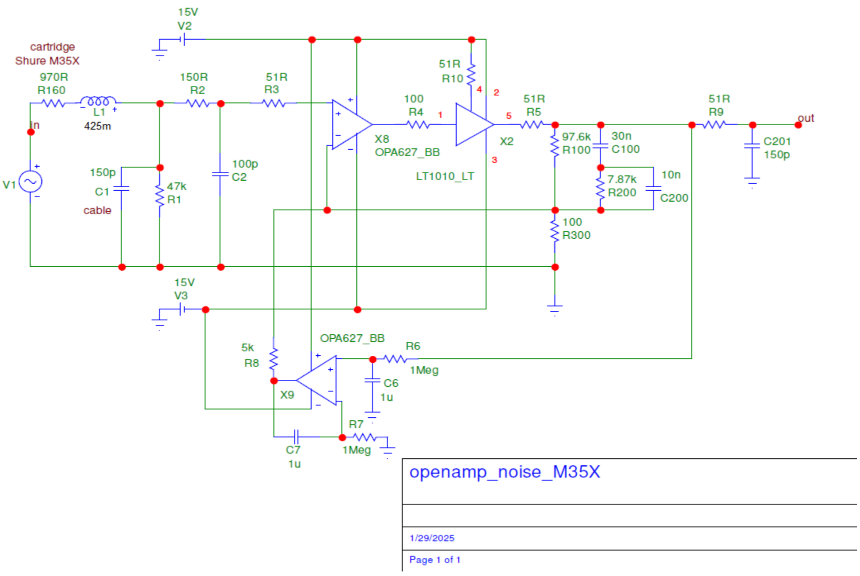
So far we have only considered resistor thermal noise and shunting impedance and have not considered the non-ideal amplifier input voltage noise and input current noise. We shall see that in case of MM cartridges the amp voltage noise is not an issue, if kept below some 5nV/rt(Hz), but current noise makes a big problem, because the input current noise flowing through R1 in parallel with R160 + L1 makes additional voltage drop - noise voltage at "out" node and is then amplified by amp RIAA EQ gain. For a typical opamp with bipolar input stage, the input current noise density is typically >=2pA/rt(Hz) and this would make 94nV/rt(Hz) on unshunted 47k resistor, compared to its 27.6nV/rt(Hz) intrinsic thermal noise. So, the contribution of bipolar opamp input current noise is almost four times bigger than the 47k resistor thermal noise!

4. Investigating real MM phono preamp by both simulation and real world measurements

For simulation and measurements I have chosen my Openamp phono preamplifier, which is an open project of the phono preamp, verified by many builders worldwide, several hundreds built.

https://pmacura.cz/openphono.htm

Schematics used in the simulations is shown below:



I have decided to compare results of the Openamp with 2 different opamps at X8 position:

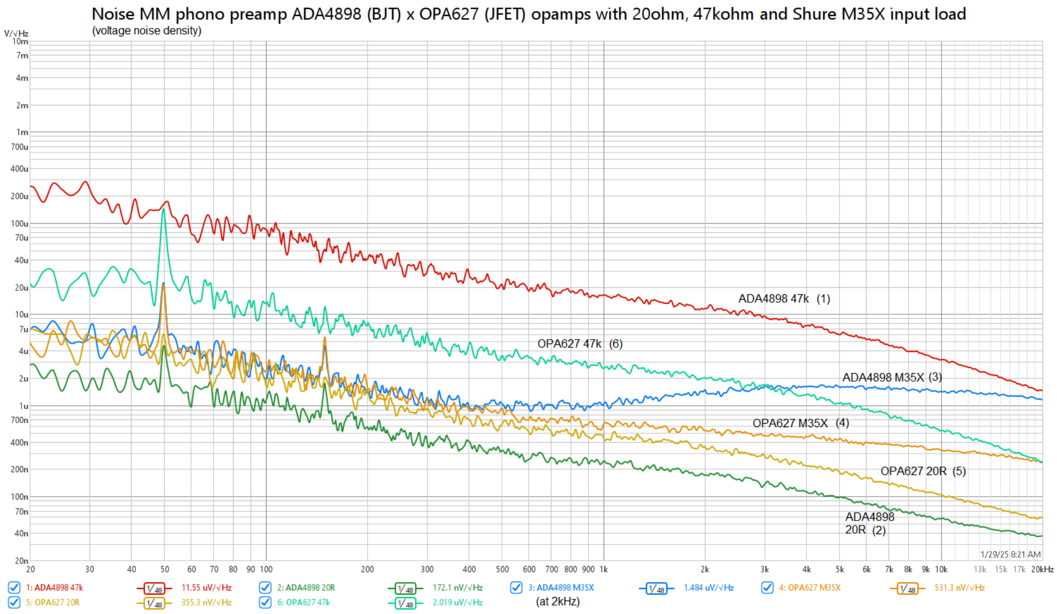
- OPA627 with JFET input, voltage noise = 4nV/rt(Hz), current noise = 2.5fA/rt(Hz),
- ADA4898 with bipolar input, voltage noise = 0.9nV/rt(Hz), current noise = 2.4pA/rt(Hz).

OPA627 has 4.5x higher voltage noise, but 1000x lower current noise than ADA4898. Both have parameters typical for very good JFET, respective bipolar input opamps. For a low noise link level preamp with low input impedance, the ADA4898 would be definitely the choice. But for a MM phono preamp? We shall see, but the answer is no. The preamp gain is 40dB/1kHz.

The noise at the output of the Openamp was measured with 2 resistors and one MM cartridge:

- 20 ohm, to simulate standard ASR SINAD measuring method with the AP analyzer,
- 47 kohm, which is the open input and worst case,
- with Shure M35X cartridge connected to the input.

Below we can see measured plots of output voltage noise with the 3 impedance cases and two different opamps, ADA4898 and OPA627.



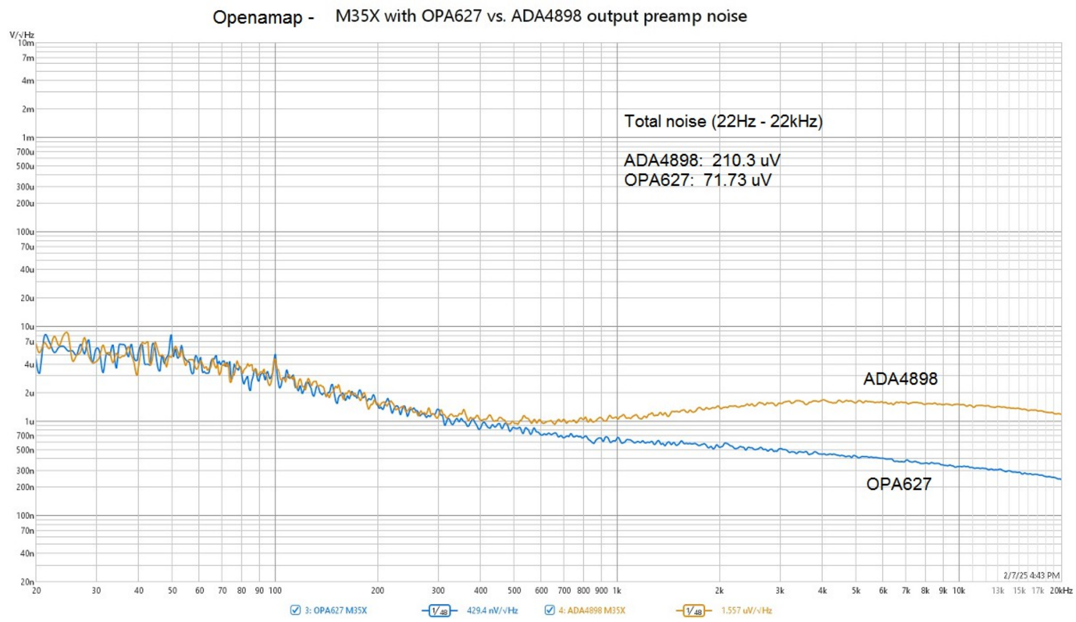
We can see that when the Openamp has 20 ohm resistor at the input (equivalent of ASR SINAD test method), ADA4898 version (bipolar opamp) has lower noise than OPA627 version (JFET) and the voltage noise density at 2kHz is about twice lower than with OPA627. *(note – mains interference spikes fixed in further plots by better shielding of cartridge and phono preamp board)*

With 47 kohm resistor, the situation is different. OPA627 version has about 6x lower noise than ADA4898 version.

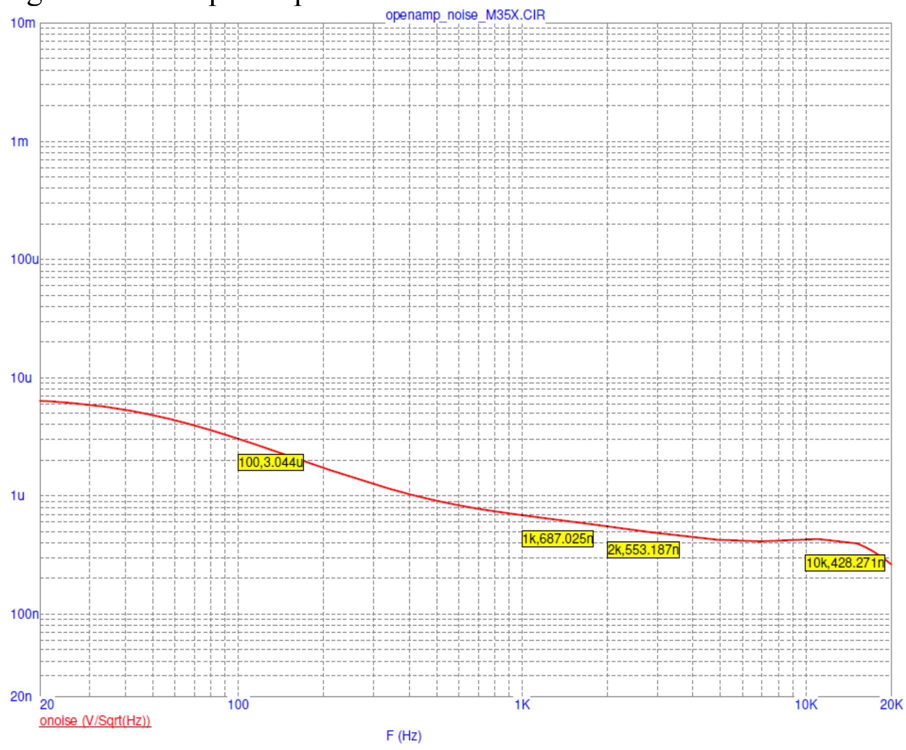
Finally, with Shure M35X at the input, the noise is almost same up to 500Hz, but above 500Hz we can see that OPA627 version is much better, with about 4x lower noise above 2kHz. So, the result from the 20 ohm ASR method would tell that bipolar AD4898 version has lower noise, however in a real world with real MM cartridge the result is just opposite. And the difference is not small.

5. Comparison of noise density and 22Hz – 22kHz total noise of both versions with Shure M35X

OPA627: 71.73uV, ADA4898: 210.3uV – 2.93x worse, 9.34dB worse. As the THD distortion with both opamps is negligible, we can reliable say that the ADA4898 version has SINAD worse of about 9dB, though it would win if tested with 20 ohm input impedance. And, should be noted, that M35X inductance is quite low and with higher inductance the difference would be even bigger.



Simulated voltage noise for Openamp with OPA627

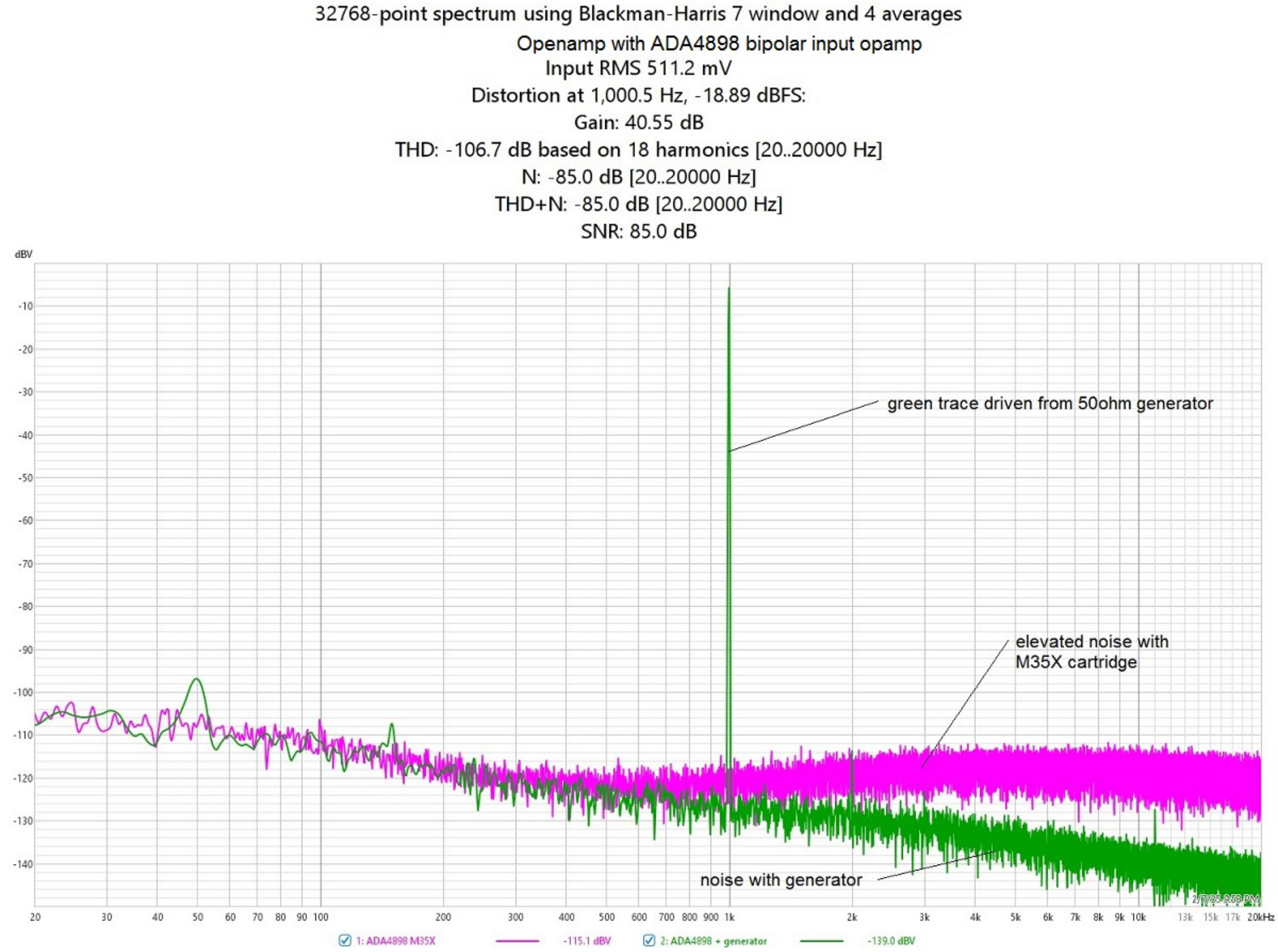


The simulated result fits very well to the measured result shown in previous image.

6. The proof of inadequacy of the method of measuring SINAD with low impedance generator

It was shown in articles #4 and #5 here that the method of driving the MM phono preamp from generator with low output impedance is incorrect, respective that it does not reflect preamp noise behavior with real world MM cartridge. Let's show it on example of the Openamp with ADA4898 driven from generator with 50 ohm output impedance. The generator output is 5mV/1kHz.

SINAD with ADA4898



Openamp with ADA4898 (bipolar input) is driven from generator with 50 ohm output impedance with 5mV/1kHz sine. SINAD /i.e. -(THD+N)/ is 85 dB. It is defined completely by noise, because THD component is only -106.7dB and then SINAD = SNR, signal to noise ratio. But, if input of the Openamp with ADA4898 is closed by M35X cartridge (instead of 50 ohm resistor), the output total noise rises to 210.3 uV and SNR = 67.5 dB. This would be the SINAD with M35X cartridge.
On the other hand, with OPA 627 the total noise with M35X cartridge is 71.73 uV and SNR = 76.9 dB.
With the input of the preamp terminated by 50 ohm we measure total noise of 47.1 uV, with OPA627. With ADA4898 it is 22.8 uV. So, from measuring method using a generator with low output impedance (like mine with 50 ohm or AP with 20 ohm) the preamp with ADA4898 has higher SINAD and is seemingly better. But, this is not the case when we connect the MM cartridge to the preamp input and the situation is instantly reversed, the OPA627 is better of about 9dB and is better in real world conditions, not in a laboratory simulated test with a low impedance generator. Thus, we cannot rely on results of the method with a low impedance generator when evaluating MM phono preamps.

7. Conclusion

With the Shure M35X cartridge, two versions of Openamp phono preamp were measured, with this result in total (22Hz - 22kHz) output voltage noise: OPA627(JFET): Vn = 71.73uV, ADA4898(bipolar): Vn = 210.3uV – 2.93x worse, i.e. of 9.3 dB worse. Calculated SINAD (ref 500mV) would be 76.9 dB with OPA627 and only 67.5 dB with ADA4898. As the THD distortion with both opamps is negligible, below -100dB, the noise component dominates in SINAD and we can reliable say that the ADA4898 version has SINAD worse of 9.3 dB, though it would win if tested with 20 or 50 ohm input impedance. And, should be noted, that M35X inductance is quite low and with higher inductance the difference would be even bigger.

The “standard” SINAD test with 50 ohm generator was performed as well and OPA627 version SINAD was 78.8 dB, ADA4898 version SINAD was 85 dB, so seemingly better and ADA4898 would win in a standard chart test as is used at ASR, however, in a real world with real MM cartridges (any) the OPA627 version is better.

How to measure noise and SINAD of the MM preamp properly:

1) Signal to noise ratio $$\mathrm{SNR} = 20\log\left(\frac{\mathrm{S}}{\mathrm{N}}\right)$$

2) Total Harmonic Distortion $$\mathrm{THD} = 20\log\left(\frac{\mathrm{S}}{\mathrm{D}}\right)$$

3) Signal-to-Noise-and-Distortion-Ratio $$\mathrm{SINAD} = 20\log\left(\frac{\mathrm{S}}{\mathrm{N}+\mathrm{D}}\right)$$

S ... signal [Vrms]
N ... noise [Vrms]
D ... distortion [Vrms]

Look at the definitions here above first:

1) Measure noise voltage at the output of the MM preamp with MM cartridge connected to its input (N)
2) Measure distortion (D) voltage when the preamp is driven from low impedance generator at 1kHz/5mV
3) Calculate SINAD from equation (3) here above.

THD and THD+N definitions in dB:

- **THD** - total harmonic distortion – defined as percentage of the square root of ratio of power sum of higher harmonics (H_2,H_3...) to the power of fundamental signal harmonic (H_1).

$$THD = 100\sqrt{\frac{H_2^2 + H_3^2 + .. + H_n^2}{H_1^2}}\ (\%) = 100\sqrt{\frac{HarmonicPower}{FundamentalPower}}\ (\%)$$

An alternative definition is frequently used:

$$THD = 100\sqrt{\frac{H_2^2 + H_3^2 + .. + H_n^2}{H_1^2 + H_2^2 + H_3^2 + .. + H_n^2}}\ (\%) = 100\sqrt{\frac{HarmonicPower}{SignalPower}}\ (\%)$$

- **THD+N** – total harmonic distortion plus noise - defined as percentage of the square root of ratio of power sum of higher harmonics and the noise power to the total signal power that also include distortion and noise power:

$$THD + N = 100\sqrt{\frac{HarmonicPower + NoisePower}{FundamentalPower}}\ (\%)$$

An alternative definition is:

$$THD + N = 100\sqrt{\frac{HarmonicPower + NoisePower}{TotalPower}}\ (\%)$$

Literature:

[1] Kester, W.: Understand SINAD, ENOB, SNR, THD, THD + N, and SFDR so You Don't Get Lost in the Noise Floor, Analog Devices MT-003 Tutorial.

[2] Mateljan, I.: Arta User Manual.