Noise performance analysis of Op-Amps in use with passive inductive transducers and inductive sensors

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Abstract – **Some medical and industrial applications use inductive source sensors. In many cases these sensors produce low voltages even lower than 0,1mV. On the other hand these sensors have significant inductance (more than 150mH and up to 1H). This paper investigates the signal to noise performance when use contemporary ultra low noise op-amps in the schematic designs without J-FET buffering. There exist very low noise op-amps with voltage noise less than the noise of 50Ω resistor but they are not suitable for inductive sources.**

Keywords – **Low Noise Amplifiers**

I. Introduction

In a previous research we discuss the design and performance of J-FET discrete input ultra low noise preamplifier with voltage noise less than 0.3nV/√Hz [1]. The circuit has significant benefits compared to the simple op-amp use but it is not suitable for some low scale and low power devices. Front transistor used in our prototype discrete input amplifier was the J-FET BF862. Unfortunately it was discontinued by NXP and stopped from manufacturing at the end of 2017. The good news is that ON Semi [2] still produces a replacement part, which uses the same footprint with signature number 2SK3557. In the previous research [1] the focus was on the parameters of the existing transistors suitable for low noise applications. Here we will discuss the op-amps suitable for the low noise applications.

The aim of this paper is to model the inductive source and to analyze the factors that produce the noise in that kind of high impedance inductive sources. The input sensor is a magnetic head that generates voltage proportional to the magnetic flux recorded on the magnetic media. Still there is lot of applications that uses that kind of media, for example the payment terminals using magnetic strip. We will investigate one of the hardest tasks – the amplification from the magnetic tape head. We will use the same source with different op-amps to analyze the signal-to-noise ratio at the output. The source parameters in the design are as follows:

- Amorphous playback head that produces voltage at reference flux of 250nWb/m; v_i=0.25mV at 315Hz;
- IEC playback time constants of τ_1=3180uS and τ_2=120uS;
- Head resistance of r_i=330Ω; head inductance of L_i=150mH;
- Amplification gain of 400 to produce 100mV at the output at reference flux of 250nWb/m for 315Hz;

We will investigate how the two major components that acts as additional noise generators takes into account: the head load impedance R_L and the negative feedback resistor R_f of the first amplifier. The schematic of the tested circuit is shown on Figure 1.

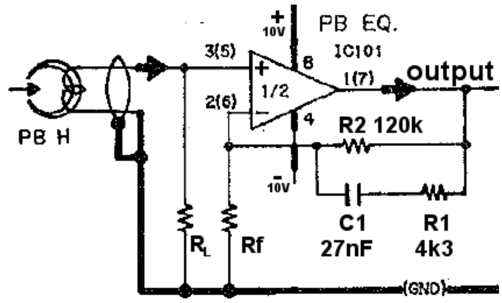

Fig. 1. Tested op-amp diagram

The self thermal noise of the resistors can be calculated by the simplified equation for the environment temperature of 25°C [4]:

$$Vn = 0.128\sqrt{R} \qquad (1),$$

where the *R* is the impedance in Ω and the *Vn* is the voltage variance in nano-volts per hertz of bandwidth. To obtain gain of 400 the value of R_f has to be 56Ω. That will produce 0.96nV/√Hz into the R_f. The load resistor R_L is more complex in the design. Its value depends but is between 220k and 47k (depending on the frequency response chart of the PB H). For the value of 220k the produced additional thermal noise will be 60nV/√Hz. For a value of 47k it will be about 27.7nV/√Hz. These values are much higher than the generated noise in the head and also are significantly higher than the voltage noise of the op-amp. In the simulation part we will investigate how the significant voltage noise of R_L contributes the design.

A. Initial research

There are many op-amps suitable for low noise applications. Some of the best known are the AD797, produced by Analog Devices [3] and LT1028 produced by Linear Technology [4]. Both use special designed BJT in the inputs. On the other hand there exist many low noise op-amps with J-FET in the inputs. They have significant voltage noise compared to the bipolar ones but the input noise current is the lowest that can be used. We will investigate the importance of the noise current (i_n) compared to the voltage noise (v_n) in the next modeling. Table 1 shows the parameters of the common known BJT low noise op-amps and includes the price per piece and the slew rate parameters, while the Table 2 shows the parameters of the low noise J-FET op-amps.

TABLE 1. LOW NOISE BJT OP-AMPS

Model	V_n [nV/√Hz]	I_n [pA/√Hz]	Slew rate V/uS	Ch	Price USD
LT1028	0,85	1,0	11	1	9,8
AD797	0,9	2,0	20	1	10,2
ADA4898	0,9	2,4	55	1/2	6
LME49990	0,9	2,8	22	1	
MAX9632	0,94	3,75	30	1	12
OPA2x11	1,1	1,7	27	2/1	11/8,3
AD8597/9	1,1	2,4	14	1/2	5,8/-
LME49710	2,5	1,6	20	1	2,3
LM4562	2,7	1,6	20	2	2,7
LME49720	2,7	1,6	20	2	2,8
AD8671/2	2,8	0,3	4	1/2	3/ 4,5
OPA27/37E	2,9	0,4	1.9/11.9	1	
NJM5534D	3,3	0,4	13	1	1
OPA2227/8	3,5	0,4	2,3/10	2	6
UPC4570C	4,5	0,7	7	2	
NE5532P	5	0,7	9	2	0,3

As can be seen most of the BJT op-amps have significant current noise. The exceptions are the OPA2227, NE5534 and the AD8671. The AD797 (Analog Devices) is a single op-amp with very low voltage noise and distortion. It appears to have been developed primarily for the cost-no-object application of submarine sonar, but it works very effectively with normal audio. The cost is something like 20 times that of a NE5532. No dual version is available, so the cost ratio per op-amp section is 40 times. This is a remarkably quiet device in terms of voltage noise, but current noise is correspondingly high due to the high currents in the input devices. Early versions appeared to be rather difficult to stabilize at HF, but the current product is no harder to apply than the NE5532.

TABLE 2. LOW NOISE J-FET OP-AMPS

Model	V_n [nV/√Hz]	I_n [fA/√Hz]	Slew rate V/uS	Ch	Price USD
AD743	3,2	6,9	2,8	1	12
AD745	3,2	6,9	12,5	1	12
OPA827	4	2,2	28	1	11
AD8655/6	4		11	1/2	
LT1792	4,2	10	3,4	1	7
MAX4575/7	4,5	0,5	2	1/2	
OPA2140	5,1	0,8	20	2	6,3
OPA637	5,2	1,6	135	1	25
LME49880	7	6	17	2	
OPA2134	8	3	20	2	4,8
NJM8502	10		20	2	
OPA2604	10	6	25	2	
NJM072	14		20	2	1,1
TL072/82	18	10	13	2	0,6

The OPA627 from Burr-Brown is a laser-trimmed JFET-input op-amp with excellent DC precision; the input offset voltage being typically ±100uV. The distortion is very low, even into a 600Ω load, though it is increased by the usual common-mode distortion when series feedback is used. The OPA627 is a single op-amp and no dual version is available. The OPA637 is a decompensated version only stable for closed-loop gains of 5 or more. This op-amp makes a brilliant DC servo for power amplifiers, it costs about 50 times as much as a NE5532, which is 100 times more per op-amp section, and about 20 times more per op-amp than the OPA2134, which is usual choice for DC servo work.

When we have different noise components we have to calculate the average noise. Adding different noise components can be done using:

$$Vs = \sqrt{V_1^{\,2} + V_2^{\,2} + \ldots + V_n^{\,2}} \qquad (2),$$

where Vs is the equivalent noise from the n voltage noise sources. We will use this equation when we make the analysis of different noise sources.

B. Modeling

The first priority is to find out the physical limits that set how low the noise can be. With a purely resistive source it is easy to calculate the Johnson noise from the input source resistance. With a noiseless amplifier this would be the equivalent input noise (E_{IN}), but real amplifiers have their own noise, and the amount by which the source/amplifier combination is noisier is the noise figure (NF). The inductive source (Fig. 2) is modeled as a resistance R_{gen} in series with a large inductance L_{gen}, and is loaded by the resistor R_{in}.

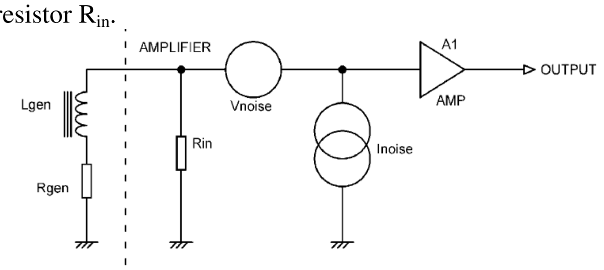

Fig. 2. The inductive source model

The amplifier block A1 is treated as noiseless, its voltage noise being represented by the voltage generator V_{noise} and its current noise being represented by the current generator I_{noise}. It does not matter which side of V_{noise}, I_{noise} is connected because V_{noise} has no internal resistance. Here V_{noise} represents not only the noise of whatever input device is used in the amplifier, but also noise generated by resistors in the feedback network.

Lets look at the source generator. The Johnson noise is generated only by the active components in its network and only by the R_{gen}. For high frequencies the impedance of the inductance is significantly higher than the active component in the source. For example the 150mH source impedance for the 18kHz is 17.3kΩ compared to the 330Ω DC resistance of the source. The first question: is that higher impedance generates additional noise component? One suspicion is that it did not generate noise but modulates the noise current that comes from the amplifier A1 and also take a part of the noise distribution of the input load resistor R_{in}. To examine that we made a practical experiment that is based on the circuit on the Figure 1. The load resistor R_{in} is 47kΩ and the used op-amp is AD797. Its parameters are shown on the Table 1. The first test was with simple resistor of 1.55kΩ in the place of L_{gen} and R_{gen}. The second experiment was with a shielded MM cartridge with the following electrical parameters: L_{gen}=650mH; R_{gen}=1550Ω. The aim of this test was to examine the total rms noise at the output of the amplifier A1. The experiment will prove if the inductance component generates additional noise in the design.

The measured noise voltage at the output of the amplifier is as follows: the pure resistor in the input with resistance of 1.55k generates 2.25mV rms at the output of the amplifier, while the inductive MM cartridge (1.55k + 650mH) generates 12mV rms in the same circuit. As a comparison the OPA2227 generates only 4.9mV rms when using the cartridge as source noise generator.

TABLE 3. PERFORMANCE OF THE FIG1 DESIGN DEPEND ON SOURCE

Op-amp / Model	Rs = 1.5k Out noise (mV, rms)	Z=1k5+650mH Out noise (mV, rms)	DC offset (mV)
OPA2140	2.0	4.2	33
uPC4570C	1.8	4.2	850
NJM2041D	1.8	4.2	580
NJM2068	1.7	4.25	400
NJM2043	1.65	4.4	40
AN6558	1.8	4.74	2300
NJM4558	3,4	4.75	620
M5220	1.7	4.8	1740
OPA2227	1.7	4.9	18
NE5532P	3.0	5.1	1100
MC1458C	6.8	7.5	1030
LME49720	2.2	8.8	600
AD797	2.25	12	5

Measurements of different op-amps in that circuit are listed in the Table 3. The table specifies the measured DC offset voltage at the output of the circuit based on Fig 1. As can be seen one of the lowest noise op-amp is the worst in the real tests. On the other hand its DC offset is the lowest compared to the other tested op-amps. The 12mV output noise of the AD797 is caused by its higher noise current and it is a proof that the inductive component of the source impedance contributes it.

Let examine the different noise components of the model in Figure 2 [5]. Finally all the noise components will be add using equation 2. All these values represent noise for 1Hz of bandwidth. The final calculation can be done for different frequency bands. The frequency determines the impedance of the source and the noise voltage produced by the input current noise.

1. The self thermal noise e_{Rgen} of the source resistance (R_{gen}) can be calculated by the equation 1.
2. The impedance seen by the current source I_{noise} increases with frequency. The increase at the top end is moderated by the shunting effect of R_{in}. This increase has a major effect on the noise behavior. The noise component from this impedance can be described using the equation:

$$e_{zi} = I_{noise} \frac{Z_{gen}.R_{in}}{Z_{gen} + R_{in}} \quad (3)$$

3. The Johnson noise generated by load resistor R_{in} is shunted away from the amplifier input by an amount that decreases with frequency:

$$e_{load} = e_{Rin} \frac{Z_{gen}}{Z_{gen} + R_{in}} \quad (4)$$

4. The proportion of noise from source R_{gen} that reaches the amplifier input falls with frequency as the impedance of Z_{gen} increases:

$$e_{gen} = e_{Rgen} \frac{R_{in}}{R_{in} + Z_{gen}} \quad (5)$$

5. A complication that is not visible in the diagram (Fig 2) is that the effective value of R_{gen} is not simply the resistance of the coils. It increases in value with frequency (while still remaining resistive – we are not talking about inductance here) as a consequence of hysteresis and eddy current magnetic losses in the iron on which the coils are wound. This has little effect on noise issues.

On top of this complicated frequency-dependent behavior is overlaid the effect of the IEC 120uS equalization.

II. SIMULATION

Clearly this simple model has some quite complex behavior. It could be analyzed mathematically, using a package such as MathCAD or it could be simulated by SPICE. The easy way is to use Excel spreadsheets using equations. The model uses 17 different spectrum bands in the range 15Hz-20kHz every band has its bandwidth and band center frequency. This divides the audio spectrum into a number of bands so IEC 120uS equalization factors can be applied, and V_{noise}, I_{noise}, and R_{gen} can be varied with frequency if desired. The frequency bands are as follows: 15Hz - 20Hz - 40Hz - 80Hz - 160Hz - 250Hz - 500Hz - 1kHz - 2kHz - 4kHz - 6kHz - 8kHz - 10kHz - 12kHz - 14kHz - 16kHz - 18kHz - 20kHz. If the frequency band of interest is not in the flat band, one must break the band into sections, calculating average noise in each section, squaring, multiplying by section bandwidth, summing all sections, and finally taking square root of the sum as follows:

$$\bar{e}_N = \sqrt{\sum_{1}^{i} e_n{}^2{}_i . B_i} \quad (6)$$

Let examine the results from the simulation. The first urgent point is to determine ideal case with ideal amplifier (self zero current and voltage noises generated by the A1). We are starting with the real source resistance of 330Ω and inductance of 150mH. The load resistor in this case has to be infinity but in practice it is about 1GΩ. The rms voltage generated by the head is about 0,25mV. The signal to noise ratio will be calculated with no A-weighting filter but the effect of the IEC 120uS equalization will be take into account. The calculated signal to noise ratio is about 65,23dB (look at the Table 4) and it is based as theoretical source limit. The signal to noise ration in this case did not change by changing the source inductance but changes when changing source resistance. For example the calculation for 3,3Ω instead of 330Ω give 85.2dB and the 1Ω source resistance give 90,26dB for the S/N. Now let put the feedback resistor Rf in the simulation. The 56Ω in the feedback will reduce the noise figure (NF) about 0,3dB for the Rin=47kΩ; 0,38dB for Rin=100kΩ and 0,48dB for Rin of 220kΩ. The bold row in the Table 4 represent the design potential limit and is marked as a reference point (NF=0dB).

TABLE 4. SOURCE NOISE FIGURE (NF) AND S/N RATIO

Condition	S/N (dB)	NF (dB)
Rgen=1Ω, 150mH, R_L=1GΩ, Rf=0Ω	90,26	-
Rgen=3,3Ω, 150mH, R_L =1GΩ, Rf=0Ω	85,20	-
Rgen=330Ω, 150mH, R_L =1GΩ, Rf=0	65,23	
Rgen=330Ω, 150mH, R_L =220kΩ, Rf=0Ω	**63,62**	**0**
Rgen=330Ω, 150mH, R_L =220kΩ, Rf=56Ω	63,14	0,48
Rgen=330Ω, 150mH, R_L =100kΩ, Rf=0Ω	62,53	1,09
Rgen=330Ω, 150mH, R_L =100kΩ, Rf=56Ω	62,15	1,47
Rgen=330Ω, 150mH, R_L =47kΩ, Rf=0Ω	61,40	2,22
Rgen=330Ω, 150mH, R_L =47kΩ, Rf=56Ω	61,11	2,51

Now it is time to add the real op-amp current and voltage noise components. Table 5 illustrates the result in the design of several op-amps of different type.

TABLE 5. OPAMP TOTAL SIGNAL-TO-NOISE RATIO

IC	S/N, dB (R_L=47k)	S/N, dB (R_L=100k)	S/N, dB (R_L=220k)
4xAD743	**60,38**	**61,26**	**62,02**
AD743	58,73	59,29	59,77
AD8671	**58,77**	**59,23**	**59,60**
OPA827	57,80	58,25	58,63
NJM5534D	57,99	58,29	58,54
OPA2227	57,79	58,07	58,32
LT1028	56,73	56,31	56,08
OPA211	53,35	52,56	52,11
AD797	52,18	51,30	50,82
LME49990	49,56	48,57	48,03
TL082	47,28	47,31	47,35

The first row in Table 5 shows the design performance of 4 AD743 JFET op-amps in parallel and this is the best practical case of the simulation the NF is only 1,6dB for 220k load impedance and is 3,24dB for the load impedance of 47k. The next row shows a single use of AD743. The best result from a single BJT op-amp is with the AD8671. It is interesting to notice that two op-amps that are referred as ultra low noise (AD797, LME49990) show the worst result. That fact is caused by their significant current noise. National Semiconductor discontinued the LME49990 at the end of 2017 probably to the fact that it is suitable only for very low source impedance designs.

III. SYNTHETIC LOAD

As can be seen from the Table 5, the load impedance R_{in} add additional noise component when using an op-amp with lower self-noise current (or using JFET op-amp). In some designs it is important to load the source with specific load impedance to ensure the frequency response chart. Typical example is the MM cartridge, where all the manufacturers specify the flat frequency response for the 47kΩ load impedance. Let look at the row 2 in Table 5. If we use load impedance of 1MΩ instead of 47kΩ the overall S/N will be 60,22dB instead of 58,73dB. That is an improvement of 1,49dB. Figure 3 demonstrate two examples that reduce the self Johnson noise of the load resistor by increasing its value on the same time the virtual load impedance still remains 47kΩ. The schematics on the right demonstrate the case where the 'A' point potential is zero.

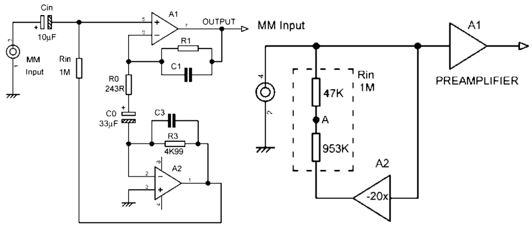

Fig. 3. Synthetic loading examples

The left circuit diagram of the Figure 3 is known as Van de Gevel circuit [6] and still supplies the virtual 47kΩ load impedance to the source. This circuit uses the current flowing through the feedback resistor R0 to drive a shunt-feedback stage around A2. With suitable scaling of R3 the output voltage of A2 is at the right level and correctly phase-inverted.

IV. CONCLUSION

The simulation model shows that the AD797, which is rated as one of the best ultra low noise op-amp, is not suitable for high source impedance. The measurements from Table 3 confirm that it is worst for the schematic on Figure 1. The comparison with the OPA2140 confirms that the AD797 is 9,1dB noisier than the OPA2140 for the input impedance of 1550Ω+650mH. On the other hand the simulation model with the same input parameters confirms that the AD797 will be 8.41dB noisier than the OPA2140. The 0,69dB difference between the simulation and the real experiment is caused by difference of the bandwidth. The simulation covers the frequency range from 15Hz-20kHz, while for the measurement is used wideband true rms microvolt meter and the frequency range was extended up to 25kHz. The practical measurement confirms the simulation very close. It can be concluded that the model is correct with its dependences.

If the design requires best noise performance then the described synthetic loading can be used or several JFET op-amps can be used in parallel reducing their input voltage noise.

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