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A Summing Configuration based Low Noise Amplifier for MPI and MPS

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Abstract: Magnetic particle imaging (MPI) is a novel tomographic imaging modality which uses static and dynamic magnetic fields to measure the magnetic response generated by superparamagnetic iron oxide nanoparticles (SPIONs). For the characterization of the SPIONs magnetic particle spectroscopy (MPS) is used. In the current research, a low noise amplifier (LNA) suitable for MPI and MPS is presented. LNA plays a significant role in the receive chain of MPI and MPS by amplifying the signals from the nanoparticles while keeping the noise induced through its own circuitry minimal. The LNA is based on the summing configuration and fabricated on a printed circuit board (PCB). Moreover, the prototyped LNA is compared with a commercially available pre-amplifier. The input voltage noise of the prototyped LNA with a receiving coil of series resistance of 0.551 mΩ and an inductance of 130 µH is 561 pV/\sqrt{Hz} with a noise figure (NF) of 11.57 dB.

Keywords: low noise amplifier, magnetic particle imaging, magnetic particle spectroscopy, noise analysis, parallelization of operational amplifiers

1 Introduction

Magnetic particle imaging (MPI) is an emerging imaging modality providing quantitative information on the spatial distribution of the magnetic particles such as superparamagnetic iron oxide nanoparticles (SPIONs) inside an object of interest [1, 2]. Moreover, MPI not only provides high sensitivity and sub-millimeter spatial resolution but the acquisition time is short allowing it to acquire real-time images. Some of the past publications [3, 4] demonstrated these parameters by acquiring 2D and 3D real-time images in in-vivo experiments. Due to these properties, MPI is an ideal technology for a number of applications ranging from conventional metabolic imaging to therapy using SPIONs [1, 5].

For the implementation of MPI or MPS, the hardware is divided into two parts, namely the send chain and the receive chain. The send chain consists of electromagnetic coils, known as transmitting coils. Depending upon the system there could be more coils such as drive field coils and selection coils. A simple MPS device usually does not have a selection field or the drive field. A receive chain generally consists of an electromagnetic coil called the receiving coil. The receiving coil detects a change in the magnetic field due to the magnetization of the nanoparticles [12]. The induced voltage in the coil has to be amplified to match the dynamic range of the acquisition system to achieve the highest resolution. The dynamic range depends on the noise floor of the device and on its specified maximum output level. The dynamic range of an analog to digital converter (ADC) is the ratio between the maximum voltage to the minimum voltage that the ADC can convert. There is also a need to attenuate the fundamental frequency induced by the transmitting coil as the amplitude of the transmission frequency is orders of magnitude higher than the signal induced by the nanoparticles. To achieve this several approaches are present such as passive filters and gradiometer coils. When the output of the analog filter matches the dynamic range of

![Fig. 1: Simplified block diagram of an MPI system.](image-url)
the LNA, then the received signal is amplified and stored in memory via ADC and is used for image reconstruction. The block diagram of the MPI setup is shown in Figure 1.

Most paramount specifications of an ideal LNA are to have a good noise figure (NF) and to provide high gains. An amplifier increases the power of both the signal and noise present at its input plus it adds the noise due to its internal circuitry. A designed LNA should minimize the noise by selecting low noise biasing conditions, therefore adding a minimum internal noise and hence able to detect even the smallest concentrations of SPIONs possible. This paper focuses on an LNA based on Operational Amplifiers (Op Amps) in parallelization, to decrease the internal noise produced by the circuitry. To demonstrate the noise characteristics of the prototyped LNA the input noise, output noise, spectral density, spectral power and NF are calculated.

1.1 Theory for Op Amp based LNA

It is challenging to deal with low amplitude signals, especially in the range lower than 10 μV (~87 dBm) and to amplify them to the dynamic range of an ADC without changing the signal integrity due to the noise produced by a system. The signal level of the higher harmonics in MPI or MPS is usually in this range or even lower. A standard amplifier configuration multiplies the input signal, the input noise coming from the system and the noise contribution of the amplifier itself, resulting in an overall worse signal to noise ratio (SNR). So overall the SNR not only depends on the input noise from the system but also due to the inherent noise of the various passive and active components present in the amplifier itself. One of the ways to improve the SNR as well as amplify the signals is to use a summing configuration. Summing configuration is just the parallelization of Op Amps. Due to summing configuration, the uncorrelated noise (amplifier noise) increases as the amplifiers in parallel add uncorrelated noise. The SNR calculation below:

\[
\text{SNR}^2 = \frac{(S_{\text{Out}})^2}{(N_{\text{Out}})^2} = \frac{(S_{\text{In}} \cdot G)^2}{((N_{\text{In}}) \cdot G)^2 + (N_{\text{Amp}})^2}
\]

For simplicity, the input noise generated by the system (if it is below the level of the particle signal) is neglected and thus the equation becomes:

\[
\text{SNR}^2 \approx \frac{(S_{\text{In}})^2}{(N_{\text{Out}})^2} \approx \frac{(S_{\text{In}} \cdot G)^2}{(N_{\text{Amp}})^2}
\]

As stated earlier, by connecting, the second amplifier in parallel there is an increase in power of the RMS signal by two times, but the increase in the RMS noise is \(\sqrt{2}\) as the amplifiers in parallel add uncorrelated noise. The SNR calculation for two amplifiers considering the above assumptions is given below:

\[
\text{SNR}^2_{\text{Two Amps}} = \frac{(2S_{\text{In}} \cdot G)^2}{0.5 \cdot (N_{\text{Amp}})^2}
\]

Theoretically, the summing configuration should solve the problem of the inherent noise generated by the Op Amps. But the proper designing of the Op Amp, as well as the selection of the Op Amp also plays a significant role. One of the foremost parameter of merit for an LNA’s inherent noise is noise density. The voltage noise density is specified in nV/√Hz and the current noise density is specified in pA/√Hz. For simplicity, these values are always referred to its input thus eliminating the gain of an LNA. The output noise of an LNA can be calculated by the average noise density given in dBm/√Hz measured by a spectrum analyzer. The formula for calculating the output noise are explained below. The values in dBm/√Hz can be easily converted to dBW by 1000 mW = 1 W; +30 dBm = 0 dBW; -30 dBW = 0 dBm. Hence the power in dBW is:

\[
dBW = \text{Measurement} \cdot \frac{dBm}{\sqrt{Hz}} - 30
\]

\[
W = 10^{\frac{dBW}{20}}
\]

\[
\text{Output Noise} = \sqrt{\text{Resistance} \cdot W}
\]

One more important parameter is the NF, it is defined as a degradation of the signal to noise ratio as it passes through a device, for example, a spectrum analyzer for a specific input noise temperature, here \(T_{in}\) is 290 K. It could be defined by the noise factor (F) which is given as:

\[
F = \frac{S_{\text{In}}/N_{\text{In}}}{S_{\text{Out}}/N_{\text{Out}}} = \frac{S_{\text{In}}/k_b T B}{S_{\text{In}} \cdot G/N_{\text{Out}}} = \frac{N_{\text{Out}}}{G T B k_b}
\]

where, \(N_{\text{Out}}\) is Noise power output, \(G\) is device gain, \(k_b\) is Boltzmann’s constant, \(T\) is Temperature in Kelvin, \(B\) is Bandwidth and \(F\) is Noise factor. To convert this formula to NF:

\[
NF = 10 \log_{10} \left( F G T B k_b \right) = 10 \log_{10} (G) - 10 \log_{10} (TBk_b) \]
It is necessary to accommodate the bandwidth of the spectrum analyzer as the noise is proportionate to the bandwidth. Therefore, the above formula can be written for the bandwidth of 1 Hz as:

\[ NF = 10 \log_{10} (F_G T B k_b) - 10 \log_{10} (G) - 174 \text{ dB} \]  

(11)

In the next section, the system design and the measurement setup is explained.

2 System Design and Measurement Setup

For the design of the LNA, the first stage consists of the LMH6629 (from Texas Instruments) an ultra-low noise, high-speed operational amplifier in non-inverting configuration. The specified input voltage noise is 0.69 nV/√Hz and the input current noise is 2.6 pA/√Hz. The second stage consists of the LT6232 (from the Linear Technology), a rail to rail Op-amp with the noise voltage of 1 nV/√Hz. In the current setup, the second stage is not used.

The simulations are performed with the LT-Spice (from Linear Technology). The OrCAD Cadence PCB solutions is used for the layout and designing. Populated circuit board (PCB) has four layers with a size of approximately 65 mm x 53 mm and consists of approx. 114 components. Figure 2 shows an image of the realized PCB without the housing and cables. A comparison of the noise power of the prototyped LNA is done with a commercially available low-noise voltage preamplifier SR560 (from Stanford Research Systems). The SR560 has a 4 nV/√Hz input noise and a bandwidth of 1 MHz. For measurement, a spectrum analyzer from Keysight (EXA-N9010A Signal Analyzer) is used. As the noise level of the SR560 falls below the noise level of the spectrum analyzer, therefore the second stage with a fixed gain of 5 is employed, to raise the level of the signal above the noise level of spectrum analyzer.

In the first test, the gain of both the LNAs (prototyped LNA and SR560 voltage pre-amplifier) is set to 20 and the inputs are terminated with a 50 Ω resistor. The measurement scheme is shown in Figure 3 below. All the measurements are performed with an resolution bandwidth (RBW) of 1 Hz with 100 averages in the spectrum analyzer. In the second test, the LNA’s are measured connected with a receiving coil with an internal resistance of \( \approx 0.551 \text{ mΩ} \), an inductance of \( \approx 130 \mu\text{H} \) and a self-capacitance of \( \approx 2.5 \text{ pF} \). For this particular measurement, the gain of the amplifiers is increased to 200 and the spectrum analyzer’s RBW is set to 10 Hz and 100 averages.

3 Results

Figure 4 shows the noise power of the LNA prototype based on the LMH6629 in comparison to the commercially available SR560 with a gain of 20. From this data, using an inbuilt function of the spectrum analyzer, the spectral density/√Hz is calculated.
The input noise and the noise figure are calculated according to the Equation 8 and Equation 11. The results are shown in Table 1. A further comparison is done by connecting a receiving coil to the input of the prototyped LNA and SR560. The RBW of the spectrum analyzer is set to 10 Hz with 100 averages. The measurement bandwidth for calculating spectrum density is set to 300 kHz starting from 100 kHz to 400 kHz.

Figure 5 shows the noise power of the prototyped LNA in comparison to SR560 with a receiving coil connected at the input. The results are shown in Table 1. In comparison to the commercially available amplifier (SR560), the prototyped LNA has around 4.78 times less input noise, when connected with the receiving coil with just 4 stages in parallel. The noise can be further reduced by increasing the number of Op Amps in parallel.

![Fig. 5: The noise spectrum of the prototyped LNA compared to commercially available pre-amplifier connected with a receiving coil.](image)

| Tab. 1: The spectral density in dBm/Hz, input noise and NF of the prototyped LNA and the commercially available SR560 with a gain of 200 with 50 Ω resistor and a receiving coil. The output noise can be calculated by multiplying the input noise with the gain. |
|-----------------|-----------------|-----------------|
| Spectral density (dBm/Hz) | Input Noise (nV/√Hz) | NF (dB) |
| Prototyped LNA (50 Ω) | -120.13 | 1.10 | 7.87 |
| SR560 (50 Ω) | -98.21 | 13.73 | 29.76 |
| Prototyped LNA (coil) | -106.40 | 0.561 | 11.57 |
| SR560 (coil) | -92.85 | 2.67 | 25.12 |

4 Conclusion

A low noise amplifier based on the parallelization is presented and compared with the commercially available pre-amplifier (SR560). The input voltage noise of the prototyped LNA is 561 pV/√Hz with a receiving coil of internal resistance 0.551 Ω and an inductance of 130 µH. The NF of the prototyped LNA is approx. 11.57 dB. Furthermore, the input voltage noise of the prototyped LNA with 50 Ω resistor at the input is approx. 1.1 nV/√Hz with a NF of approx. 7.87 dB. In future, the plan is to test and calculate the current noise and to reduce the noise level further by increasing the parallelization of Op Amps.

Author Statement

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References