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AN INTERFACE FOR NERVE RECORDING AND STIMULATION WITH CUFF ELECTRODES

Mesut Sahin, *Student Member, IEEE,* Dominique M. Durand, *Member, IEEE*
Applied Neural Control Laboratory, Department of Biomedical Engineering
Case Western Reserve University, Cleveland, OH 44106-4197
E-mail addresses: mxs44@po.cwru.edu, dxd6@po.cwru.edu

***Abstract*—A nerve cuff electrode interface capable of both stimulating and recording from a nerve is described. The interface also rejects the EMG contamination in the recordings using reactive components without adding noise to the ENG signal. A transformer is added to the design for noise matching and the signal-to-noise ratio improvement is evaluated for a specific amplifier (AMP-01).**

INTRODUCTION

Electroneurogram (ENG) signals recorded from peripheral nerves using cuff electrodes are very small, sometimes in the order of a few micro volts, and the electromyogram (EMG) contamination from the surrounding muscles is a few order of magnitude larger. A monopolar cuff design[1] and the use of a potentiometer for balancing the contact impedances [2] have been suggested to reduce the EMG contamination. In this paper, we present a transformer interface that reduces the EMG contamination and also allows simultaneous stimulation of the nerve while recording its activity. We compare the new design with the standard tripolar configuration for EMG rejection and the SNR. Another transformer is added to the design to improve the signal-to-noise ratio (SNR) of the ENG recordings by noise matching.

DESIGN CONSIDERATIONS

The new interface design is shown in Figure 1. The resistances R_1 through R_3 represent the impedances measured between the contacts of the cuff electrode and a distant reference. The voltage sources simulate the potential differences that are induced at each contact against the reference electrode by the EMG and ENG activities. The EMG signals are assumed to be symmetrical with respect to the reference and the ENG activity is assumed to induce a potential only at the central contact. Transformer TR_1 is used for both rejection of EMG signals and stimulation of the nerve through the end contacts (R_1 and R_3). Transformer TR_2 is used to match the source resistance to the noise characteristics of the input stage of the amplifier (AMP-01) to maximize the SNR.

In the standard tripolar configuration (Figure 2), the EMG signal is entirely canceled only if the signal amplitudes induced on each half of the cuff by the EMG activity are the same and the impedances of the end contacts (R_1 and R_3) are identical. A small imbalance in the contact impedances can cause a large EMG contamination in the ENG signal. Adding the tightly coupled coils L_1 and L_2 ($n_1=n_2$) with large reactive impedances in series to the end contacts (Figure 1) can help eliminate the imbalance problem without adding another source of thermal noise. The total source impedance is not increased by L_1 and L_2 (which would otherwise degrade the SNR due to the input current noise (i_N) of the amplifier, see figure 3) since the transformer TR_2 ideally presents no impedance to the ENG currents. That is, unlike the EMG currents, the ENG currents flowing through L_1 and L_2 generate magnetic fluxes in opposite directions in TR_1 and they cancel each other out. This transformer is also used to deliver currents to the nerve through the end contacts for the activation of the nerve. Ideally, the two identical but opposite polarity currents (I_{L1} and I_{L2}) induced inside L_1 and L_2 by the stimulus current applied to L_3 cancel each other out and do not develop any potential across R_2 and TR_2, which would otherwise be observed as a stimulation artifact at the output. This should be true even though the contact/nerve impedances are not equal. The fast-recovery diode (1N914) is used to provide a path for I_{L3} after the stimulus is turned off.

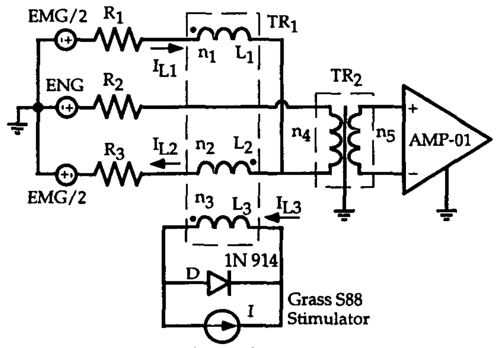

Figure 1: The new interface design for nerve cuff electrodes.

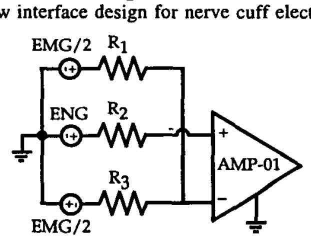

Figure 2: The standard tripolar configuration.

Now we apply the concept of **noise matching** to the amplifier AMP-01 (Precision Monolithics Inc.) and compute the SNR improvement that can be gained using a transformer. The intrinsic noise of an amplifier, which is mostly due to the shot noise generated at its input stage, can be modeled with equivalent voltage (e_N) and current (i_N) sources as shown in Figure 3. Matching the internal resistance (R_S) of the signal source (e_s) to the ratio of e_N over

i_N using a transformer is called noise matching and it maximizes the SNR at the output [3]. Note that matching Rs to the input impedance of the amplifier, which is called **power matching**, does not necessarily increase the SNR. The optimal source resistance and the optimum turn ratio for the transformer are given by the following equations:

$$R_{SO} = \frac{e_N}{i_N} \quad \text{(Equ. 1)} \qquad n = \sqrt{\frac{R_{SO}}{R_S}} \quad \text{(Equ. 2)}$$

The e_N and i_N values for AMP-01 (measured at a single frequency) are 5 nV/√Hz and 0.15 pA/√Hz, constant between 10Hz-10kHz. Then, the equation 1 dictates that the optimum source resistance for AMP-01 is 33.3 kΩ. The SNR improvement that can be gained by using a transformer can be computed for a given source resistance by taking the ratio of the SNRs with and without the transformer.

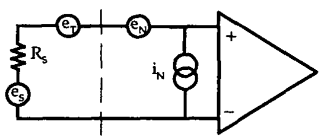

Figure 3: Equivalent voltage and current sources to model the thermal noise (e_T) of a signal source (e_s) and the shot noise of an amplifier.

The SNR improvements gained with noise matching for a range of source impedances are shown in Figure 4 for AMP-01. Note that below 1.31 kΩ, SNR improvements of greater than 2 (100%) can be obtained theoretically.

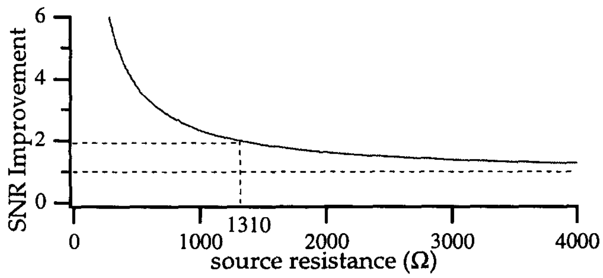

Figure 4: The signal-to-noise ratio improvements gained with noise matching for the amplifier AMP-01 for a range of source impedances.

EXPERIMENTAL RESULTS

Unequal values for the resistors R_1 through R_3 are chosen to simulate an imbalance in the contact/nerve impedances (R_1=1.5 kΩ, R_2=1 kΩ, R_3=0.5 kΩ). PICO 24500 (audio transformer, PICO Electronics Inc., n3/n1=n3/n2=10, $X_{L1}=X_{L2}$=6.6 kΩ at f=500 Hz) was arbitrarily chosen for TR_1 to demonstrate the EMG rejection effect. The gains of the new design and the standard tripolar configuration were measured for both ENG and EMG signals using sinusoidal signal generators at 500 Hz, a frequency at which the ENG and EMG spectra overlap. The EMG rejection ratio, which is defined as the ratio of the ENG gain over the EMG gain, is measured as 41.3 and 4.4 for the new design and the tripolar configuration, respectively. Thus, the new design improved the EMG rejection ratio by a factor of 9.3 (19.4 dB).

Stimulations (pulse width 100 μsec) were applied through transformer TR1 that resulted in a current amplitude of 1 mA in L_1 and L_2. A plot of stimulus artifact recorded at the output of the new design (ENG gain is 1000) is shown in Figure 5. Although the stimulation artifact is large due to the high gain, the output voltage returns to the zero level within a few milliseconds after the stimulus. With this short lasting artifact, ENG activity can be sampled between the stimuli even at relatively high stimulation frequencies.

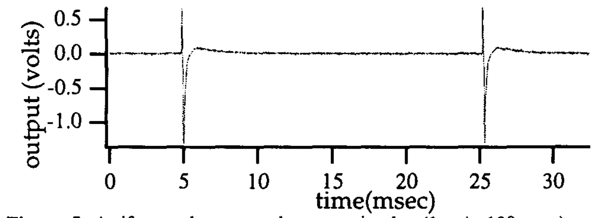

Figure 5: Artifact at the output due to a stimulus (1 mA, 100 μsec) at an overall ENG gain of 1000.

The SNR improvement gained with noise matching was measured for a source resistance value of 1.33 kΩ ($R_1=R_2=R_3$= 888 Ω). The optimum turn ratio (n) for the transformer was found to be 5 for this value of the source resistance (equation 2). Thus, PICO 24500 (audio transformer, Pico Electronics, Inc.) was used for TR_2 with the two secondary coils connected in series. The input-referred noise, which is the output noise divided by the gain, of the new design (Figure 1) and the standard tripolar configuration (Figure 2) was measured as 0.35 μV_{rms} and 0.56 μV_{rms}, respectively. Thus, the SNR improvement provided by the transformer was about 1.6 (60%). The theoretical SNR improvement for the value of the source resistance was %98 (figure 4).

DISCUSSION

The EMG rejection ratio of the new design relies on the reactive impedances of the coils L_1 and L_2. Larger EMG rejection ratios can be obtained by choosing a transformer with larger reactive impedances within the EMG frequency band. The advantages of this EMG rejection method are that it does not require tuning, it does not add thermal noise to the signal, and it tolerates large imbalances in the contact/nerve impedances. The circuit also has the other advantages of the transformer interfaces such as filtering and electrical isolation.

CONCLUSION

The new nerve cuff interface design improves the EMG rejection ratio of the recording system over the standard tripolar configuration and it allows simultaneous stimulation of the nerve while recording its activity. The use of a noise matching transformer can provide significant SNR improvements in the nerve cuff recordings made with AMP-01 amplifier for small cuff/nerve resistances.

REFERENCES

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