— INSTRUMENTATION & TECHNIQUES —

Automated offset compensation for DC biopotential measurements

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We describe a design for high-gain DC bioamplifiers with automatic offset nulling capability. Taking advantage of state-of-the-art commercially available linear integrated circuits, the design is suitable for low-level measurements such as EEG and event-related potentials. DC input offsets can be nulled instantly, making multichannel DC amplification feasible without time-consuming manual offset compensation. In addition, both signal and DC offset outputs are provided, permitting concurrent monitoring of slow large-scale DC shifts as well as faster small-signal activity. An alternative AC mode with signal and offset outputs is also provided. This approach lends itself to a wide range of applications in which small DC biopotentials must be measured in the presence of larger, variable DC components.

DC biopotentials have been gaining increasing importance in clinical and experimental work (Bauer & Lauber, 1979; Bulow et al., 1987; McCallum, Cooper, & Pocock, 1988; Morrell & Nelson, 1987). However, reliable measurement of multichannel DC signals continues to be a problem, primarily due to methodological difficulties. This is because the operational complexity of operating a DC bioamplifier becomes completely unmanageable when more than one or two amplifiers are employed. This report describes an amplifier design that significantly reduces the operational burden while providing essentially equivalent electrical information, thus facilitating the measurement of multichannel DC biopotentials. The technique is therefore particularly well suited for use in automated or computerized systems.

The measurement of a DC potential is not a problem per se; the difficulty lies in compensating for drift and other slow changes that are not considered part of the signal of interest. For example, electrode polarization can lead to bias voltages, which drift and saturate high-gain amplifiers. This situation is complicated by the fact that DC phenomena of interest are often very small signals that are superimposed upon larger, unstable bias voltages. If any stage of the amplifier cannot either tolerate or re-

move these offsets, that stage will saturate, and the output will fail.

Therefore, conventional AC amplifiers (Figure 1) provide capacitor coupling at the input to block the input offsets. These large-signal components are thus lost immediately, and they cannot be recovered. In addition, any mismatch between the coupling components at the input will degrade the common-mode rejection ratio at frequencies near the low cutoff (Wogan & Michael, 1988). One way to eliminate saturation is to operate DC amplifiers at low gain. However, this makes it difficult to measure small DC shifts. For example, very slow EEG changes of tens or hundreds of microvolts have been shown to reveal important psychological and physiological events (Caspers, Speckmann, & Lehmenkuhler, 1980; McCallum et al., 1988). However, electrode offsets associated with surface measurements may be hundreds of millivolts, and they can also produce large drifts.

The general approach to managing such situations is to manually null out the offending potentials. Many amplifiers provide polarity and range switches and a multi-turn potentiometer for this purpose; through reading the positions of these adjustments, one can calculate the offset, providing an instantaneous measure of the total signal. However, this may take several seconds or even minutes, especially in the presence of changing offsets. Clearly, manual offset compensation is not practical in multichannel systems, particularly if the system must be balanced often, as in multiple trial protocols.

For these reasons, many biopotentials, particularly EEG, have traditionally been measured in the AC mode, with low-frequency cutoffs ranging from 0.01–2 Hz. Even in the AC mode, if long time constants are used, offset nulling can be required in order to stabilize the amplifiers (Walker & Kimura, 1978).

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"STANDARD" EEG - AC COUPLED

Figure 1. Conventional AC-coupled EEG measurement: This illustrates the use of capacitor coupling on the input, to remove offset potentials present at the inputs. The high-frequency components in the signal can then be measured with high precision; however, the DC part of the input is irretrievably lost.

DC EEG WITH OFFSET OUTPUT

Figure 2. DC EEG measurement with offset output: The input offsets are removed at the command of a control signal, which causes the amplifier to bring its output to zero. The high-frequency signal and the offset voltage are available as separate outputs.

DC Offset Removal - Conceptual Design

Figure 3. Conceptual design for DC offset removal: This circuit develops an internal offset voltage that can be used to balance the amplifier when the offset zero command is issued.

Our approach provides a precision DC amplifier suitable for such applications. It combines a high-quality instrumentation input with remote autozeroing capability. It also provides an independent offset output, which reflects the "bucking voltage" presented to the input stage (see Figure 2). The offset output is useful for monitoring the condition of electrodes, or for measuring other DC potentials that accompany small signals of interest. This method, therefore, allows the input offset and drift information to be measured, rather than simply discarded.

The amplifier can be zeroed at any time, via a remote switch closure, or TTL or computer D/A pulse. In addition, the circuit can operate in an AC mode, while preserving the offset output. In either mode, the design effectively deals with the measurement of AC and DC signals in the presence of large and variable unwanted DC components. The conceptual design is shown in Figure 3. A low-pass filter tracks the DC component of the output and derives an offset reference voltage. Since this offset voltage is the inverted low-frequency or DC component of the signal, it can be added to the input stage to yield the unsaturated small-signal component without sacrificing the relatively larger DC information. A sample-and-hold circuit is used to capture and hold the offset, and to present it as a reference voltage to the input amplifier when nulling is required. This approach operates the input amplifier near the center of its operating range for maximum accuracy, and it prevents saturation of the input stage while preserving the DC information.

Under user control, this new reference voltage is acquired and held, and the amplifier rezeros itself and continues operating with the new offset. This offset is maintained until the next rezero command is issued. In the implementation described here, the input is constructed from Precision Monolithic (PMI) AMP-01, SMP-10, and OP-90 linear integrated circuits (Figure 4). The AMP-01 Precision Instrumentation Amplifier provides a unique reference input that effectively floats its output on a given voltage, providing the required signal summation. The SMP-10 is a monolithic sample-and-hold circuit that provides fast voltage acquisition and very low leakage current on the storage capacitor. Leakage is typically 0.05 nA,

producing in this design a 5 $\mu\text{V}/\text{sec}$ droop at the offset output; referred to the input, this is .05 $\mu\text{V}/\text{sec}$, or 3 $\mu\text{V}/\text{min}$. The OP-90 provides operational amplification with very low offsets, noise, and power consumption.

Since the low-pass filter is cascaded with a sample-and-hold circuit, the DC component of the filter is stored, and the circuit thus remains DC coupled, using as its offset voltage the offset that was last present on the filtering capacitor. The relevant signals are shown in Figure 5. The circuit operation in this mode is similar to a design reported by Bauer, Steininger, and Schock (1980), who used a D/A converter in a network to achieve the compensation. This design avoids the cost and quantization error associated with the D/A, plus provides an additional AC mode, which can be described as follows:

When the sample-and-hold circuit is bypassed, the circuit becomes an AC-coupled amplifier with conventional bandpass characteristics, but with the additional capability of providing an offset output. This output contains all components of the input signal that are not provided at the primary output. The AC-mode circuit is actually a special case of a general method of inverting the transfer function of a linear network. In this case, the overall circuit becomes a high-pass filter by virtue of its having a low-pass filter included in the negative feedback path. Specifically, if the transfer function $T(s)$ is given by:

$$T(s) = 1/(1+sRC),$$

where RC is the low-pass filter time constant, then the transfer function of the entire circuit becomes

$$\begin{aligned} \text{Output/Input} &= 1 - T(s) \\ &= sRC/(1+sRC), \end{aligned}$$

which effectively converts the low-pass characteristic to high-pass. This, then, provides the functional equivalent of AC coupling without requiring the placement of capacitors in the signal path. Thus, when the circuit is used in the AC mode, the two outputs provide signals that can be sampled separately. This allows the investigator to measure the high-frequency information with high absolute precision, while simultaneously measuring the lower

Figure 4. Design for autozeroing DC-coupled differential amplifier; practical implementation of Figure 3, using commercial ICs, providing a preamplifier with gain of 100.

Figure 5. Internal signals, DC autozeroing mode: from top, A = Presumed input signal; DC component of original signal; C = reference voltage applied to preamplifier; D = output of autozeroing amplifier; B = inverted version of original signal; E = offset voltage developed within amplifier.

frequency baseline with a lower, but still appropriate, precision.

Clearly, the choice of the RC time constant affects the performance of this circuit. This parameter has an important effect on the voltage level that is actually sampled and applied as the offset correction. In our application, we have chosen $RC = 0.16$ sec. In the AC mode, this is equivalent to a low cutoff frequency of 1.0 Hz. For typical EEG signals, this allows the circuit to follow baseline shifts without reflecting shorter term changes such as delta waves. Other choices of RC may be suitable for other applications. In situations where the design tradeoffs are critical, it may be desirable to use a second or higher order filter, to attain a rapid response time with minimal overshoot.

An additional advantage of this approach is that the output of the first-stage amplifier remains at the center of its operating range, providing superior linearity and operating margin. The approach also eliminates the requirement for capacitors in the input path. As a result, the input resistance can be very high—up to the 10 G Ω limit of the AMP-01 at typical gains. Note that the small AMP-01 output offset voltage is nulled along with the other internal circuit offsets, as part of the one-time nulling operation that uses the null inputs of the SMP-10.

The input stage has a gain of 100 and a full-scale operating range of 20 V peak-to-peak, so that a total input off-

set of up to 100 mV can be tolerated before the input saturates. This is the maximum offset that can be balanced out. During normal operation of the amplifier, the input stage never saturates, even if the output is allowed to saturate. Typically, a second stage provides a gain of 100 to 5,000, providing a total gain of 10,000 to 500,000. If the total gain is 10,000 and a full-range output of 10 V p-p is used (typical for laboratory systems), the output will have a range of $\pm 1,000$ μ V before the amplifier must be reset. Therefore, this design provides an operating range of ± 100 mV, within which we can automatically and instantaneously locate a full-scale window with a range of $\pm 1,000$ μ V, and 100 times higher resolution (Figure 6).

The DC mode with resetting is most useful in discrete-trials designs, such as are typically used in event-related potential studies. The two outputs then give separately useful microvolt-resolution signals for measuring within-trial events, and millivolt-resolution signals for measuring between-trial variations. It is important to note, however, that since the two signals are measured with different precisions, it is not possible to precisely reconstruct the original signal by combining them. Nonetheless, this method is valuable in that it allows important offset and drift information to be measured rather than simply discarded.

For example, the microvolt signal can be digitized with 10 bits plus sign, providing 0.98 μ V per bit resolution. At higher overall gains, greater resolution is of course possible. If the offset channel is then similarly digitized, providing 98 μ V per bit, this data can be used to estimate the total signal. This procedure locates the $\pm 1,000$ μ V measurement window with an accuracy of $\pm .5$ LSB, or 98 μ V. However, the total precision of the measurement cannot be finer than that of the coarser component. Thus, the residual uncertainty in the offset measurement precludes reconstruction of the entire input signal with the same precision as the microvolt-level output.

AUTOZERO AMPLIFIER SIGNAL RANGES

Figure 6. Signal ranges for DC autozeroing amplifier: left, total capture range of amplifier input, with small-signal window positioned inside; right, small-signal window, amplified to full-scale gain.

AUTOZEROING DC-COUPLED ISOLATION AMPLIFIER

Figure 7. Isolation amplifier incorporating autozeroing: The autozeroing preamplifier is embedded within an isolated front end, providing safety and noise immunity.

Regardless of how far out of range the output has moved, resetting will always be instantaneous and accurate. As long as the input stage never saturates, accurate offset values are available. However, if the input offset exceeds the maximum value tolerable at the input, rezeroing will not be possible, since the input stage will be saturated, and no further signals can be measured. Compared with capacitor coupling, where the input capacitors can "buck" an arbitrary large voltage, this design limits the offset that can be cancelled.

In order to allow a large range of offset compensation, the input gain must be lower than in typical AC designs so as to prevent amplifier saturation. In exchange for this limitation, the design provides the advantage of having the precise bucking voltage available as an output, thus providing more information than a conventional AC-coupled amplifier. An additional advantage of this configuration, versus conventional AC-coupled amplifiers, is that the effective AC coupling is performed after the differential-to-single-ended conversion is achieved. As a result, common-mode rejection is not degraded by possible mismatch of the components that produce the AC coupling at each input.

The design lends itself to control of multiple channels, either individually or in unison. The offset compensation circuit resides in the input stage, typically draws less than 12 mA, and can be powered by an isolated power supply, which can be provided by the second amplifier stage. Each channel has an independent reset circuit. Therefore, even when channels are operated in unison, there is no interaction between them.

The preamplifier design shown here can be constructed for a component cost of approximately \$75 per channel, not including a power supply. It is necessary to provide

additional gain of approximately 1,000, depending on the application specifics. This preamplifier has been successfully combined with Analog Devices Type 286J and 292A Isolation Amplifiers to provide complete EEG amplification, plus isolated power for each preamplifier.

For patient safety and noise immunity, we have magnetically isolated the signal output and the offset output, and optically isolated the control signal, so that each amplifier has its own isolated power supply and ground (Figure 7). Our laboratory system also includes an out-of-range indicator circuit, which signals whenever one of the channels exceeds normal operating ranges, indicating the need for resetting. The total component cost for this system is approximately \$400 per channel, including circuit boards, power supply, polygraph pen interface circuit, front-panel controls, and enclosure. We can provide additional circuit details, circuit boards, and construction details to interested investigators who contact the primary author.

Figure 8 shows the operation of 4 channels from a 16-channel system, currently in use for studying DC EEG event-related potentials. At the beginning of the trace, the amplifiers are operating with the last offset null still in effect. At the beginning of a trial, marked by the beginning of the timing pulses, the amplifiers are reset in unison, thus returning to the zero baseline. Ten seconds of EEG are gathered, in DC-coupled mode. At the end of the trial, the amplifiers are again zeroed, as a convenience to prevent saturation, and to permit continuous monitoring of the outputs. In an experimental paradigm with many trials, the amplifiers are reset hundreds of times in one session.

A 16-channel system based on this design has been in use for over a year, and it has provided hundreds of hours

DC EEG for Event-Related Potentials

Figure 8. DC EEG event-related potentials in autozero mode: four EEG channels acquired in DC-mode, with automated offset compensation both at the beginning and at the end of the trial; event-marker channel indicates presentation of stimulus material, and subject's response.

of DC biopotential recordings. To perform these measurements with conventional DC amplifiers would have required excessive monitoring and adjustment, rendering the experiments impractical. An additional project is planned to measure shifts in cortical potentials, using invasive electrodes placed during neurosurgery, and during long-term epilepsy monitoring. Again, it is hoped that this method will permit the measurement of DC brain potentials that would otherwise be unavailable.

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