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A Review On CMOS-Based Operational Transconductance Amplifiers For Biomedical Applications

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ABSTRACT

The operational transconductance amplifier (OTA) is a fundamental analog processing block widely utilized in various applications. In recent years, the development of CMOS-based OTAs with ultra-low power consumption, low voltage operation, and enhanced linearity has gained significant attention, particularly in biomedical applications. This review explores the relationship between power consumption and linearity in CMOS OTAs for low-frequency biomedical applications, as reported in various literature sources. A comparative analysis is presented based on key performance parameters such as linearity, technology, supply voltage, power consumption, operating frequency, and their suitability for biomedical signal processing. This study aims to provide valuable insights for future researchers in optimizing OTA design for improved linearity, energy efficiency, and biomedical applications.

Keywords: CMOS, Operational Transconductance Amplifier (OTA), Biomedical Signal, Low Frequency, power consumption, EEG, ERG, ECG, EMG, Biomedical Applications.

1. INTRODUCTION

The field of biomedical electronics is evolving rapidly with advancements in technology and innovative projects. Modern biomedical devices are designed to be highly functional, accurate, compact, and easy to use. However, power consumption has become a major challenge, especially for portable biomedical devices that rely on battery life. These devices need to operate efficiently while maintaining a low-noise response, as biomedical signals are often weak and sensitive to interference [1], [2]. With the rapid development of microelectronics, there is an increasing demand for small, precise signal measurement modules, especially for implantable biomedical devices. Monitoring various biomedical signals, such as the electrocardiogram (ECG), electromyogram (EMG), and electroencephalogram (EEG), plays a crucial role in healthcare. These signals provide vital information about a person's health, helping doctors diagnose medical conditions related to the heart, muscles, and brain [3]. Biomedical applications like ECG and EEG require highly power-efficient designs since most portable biomedical sensors run on batteries. ECG and EEG are two of the most critical components in biomedical monitoring systems, as they help assess the functions of the heart and brain. To capture these signals, analog processing circuits are needed. These circuits connect to the body through electrodes and record electrical activity. Many integrated circuits (ICs) have been developed for this purpose, and one of the most important components in these ICs is the low-pass filter. In ECG and EEG systems, the cutoff frequency of these filters typically ranges from 200 Hz to 250 Hz. Different filtering techniques, such as Gm-C, Active-RC, OTA-C, and switched-capacitor filters, can be used depending on the frequency and design requirements [4], [5].

Designing low-frequency circuits is challenging because it requires a very low transconductance (Gm) in the range of nanoamperes per volt (nA/V) and capacitors larger than 100 pF. However, many semiconductor foundries cannot provide capacitors larger than 50 pF due to space limitations. Additionally, circuits with such low transconductance values often suffer from increased noise, distortion, and other imperfections, making the design process even more complex [6]. CMOS Operational Transconductance Amplifiers (OTAs) are specialized analog circuits that convert an input differential voltage into an output current. The core principle of CMOS OTAs is based on the transconductance (gm) of MOSFET devices. In simple terms, transconductance measures how effectively a small change in the input voltage can generate a change in the output current. This property makes OTAs an essential component in analog signal processing, especially in low-power applications [7], [8]. CMOS OTAs function as voltage-controlled current sources, meaning that the output current is directly related to the difference between two input voltages. The factor that determines this relationship is the transconductance (gm), which can be adjusted by controlling the biasing current of the MOSFETs. By changing the bias conditions, designers can tune the transconductance and modify the gain of the OTA to meet the specific requirements of different applications. This tunability makes OTAs highly adaptable to a wide range of circuit designs [9], [10]. A key feature of CMOS OTAs is their differential operation, which significantly improves circuit performance and reliability. This configuration offers two major advantages. First, it provides noise reduction, as differential operation cancels out common-mode noise, making the circuit more resistant to external interference. Second, it improves linearity, allowing the amplifier to process signals with minimal distortion. This is especially important in biomedical applications, where signals such as ECG and EEG are often weak and need precise amplification for accurate diagnosis [11]. CMOS OTAs are highly versatile due to their ability to generate a controlled current output from a differential input voltage. This makes them useful in various analog signal processing tasks, such as filtering, amplification, and modulation. In biomedical devices, filtering helps isolate specific frequency components, amplification strengthens weak bio-signals, and modulation enables efficient signal transmission. Due to their adaptability, CMOS OTAs are widely used as fundamental building blocks in biomedical systems, improving the performance, accuracy, and energy efficiency of medical devices.

2. LITERATURE REVIEW

Jangam et al. [12], designed an ultra-low-power OTA for biomedical applications using 0.18μm CMOS technology with a bulk-driven (BD) approach to reduce power consumption. The OTA operated at 0.8V, consumed only 5.5pW, and achieved a 70dB gain, making it suitable for implantable and wearable sensors. The study compared the design with conventional OTAs, showing significant improvements in gain and power efficiency. Additionally, the use of a current-reuse OTA with a low-noise capacitor feedback amplifier enhanced ECG signal processing. The current-reuse scheme with a differential input CMOS inverter further reduced noise and improved performance in biomedical applications. Soni et al. [6] presented a novel OTA design for low-frequency biomedical applications, particularly for ECG signal processing. The design was implemented using 90nm CMOS technology with a ±0.35V power supply. It achieved an operating frequency of 250 Hz and had a very low power consumption of 5.98 nW. Jusoh et al. [13], designed and analyzed a current mirror OTA for biomedical applications using 45nm and 90nm CMOS technology. The 45nm OTA demonstrated superior performance with an open-loop gain of 45dB, CMRR of 93.2dB, and low input-referred noise of 1.113 $\mu V/\sqrt{Hz}$ at 1Hz, while consuming only 28.21nW of power from a ±0.5V supply. Its low power consumption makes it ideal for bio-potential signal detection, especially in ECG signal processing. Laoue et al. [14] designed an ultra-low-power telescopic OTA using the bulk-driven technique. Their design was implemented using CMOS 180nm technology with a ±0.5V supply voltage. The achieved bandwidth was 250 Hz, and the power consumption was 386 nW. Gracia et al. [15] proposed a low-power and low-noise OTA for cardiac implantable medical devices used for heart activity monitoring. Their design, based on 45nm CMOS technology, achieved a gain of 51 dB while operating at a 1V supply voltage, with a power consumption of 11.9 μW. Rodrigues et al. [16] developed a low-power and very low-transconductance OTA for biomedical applications. The design was based on the series-parallel gate-driven technique and was implemented using Cadence software with 180nm CMOS technology. The OTA operated at a 1.6V supply voltage, with a transconductance of 24.63 nS and a power consumption of 194.33 nW. Telnaz Zarifi [17] discussed the increasing demand for real-time personal medical monitoring and the need for efficient medical equipment. The study focused on EEG monitoring systems, which are essential for applications like epileptic seizure prediction and brain-computer interfaces (BCI). A low-power EEG signal amplifier was designed using 90nm CMOS 1P9M technology, with a 1.2V supply voltage and power consumption of 3.6 μW. The amplifier covered a frequency range from 0.1 Hz to 10 kHz, making it suitable for portable EEG monitoring systems. Jangam et al. [18], developed an ultra-low-power OTA using 0.18μm CMOS technology for biomedical applications. The bulk-driven design operated on a 0.8V supply, consuming 5.5pW power with a 70dB gain, making it ideal for implantable and wearable sensors. Compared to conventional OTAs, it demonstrated higher gain and lower power consumption. A current-reuse OTA with a low-noise capacitor feedback amplifier was also introduced for ECG signal processing, utilizing an inverter-based differential input stage to enhance noise-power efficiency.

3. BIOMEDICAL SIGNAL PROCESSING SYSTEM

One of the most important components of a biomedical system is the analog processing unit, which includes a preamplifier and a filter. The most commonly used filter for processing biomedical signals is based on an Operational Transconductance Amplifier (OTA), as biomedical signals operate at very low frequencies.

The preamplifier plays a crucial role in amplifying the input signal to a higher level while minimizing noise and distortion. For example, in electrocardiograph (ECG) applications, the preamplifier must enhance the signal to around 100 millivolts, typically using a low-pass filter. High-performance, ultra-low-frequency filters can be efficiently designed using CMOS technology [1]. Biomedical signals play a crucial role in monitoring and diagnosing various physiological activities of the human body. Some of the most commonly used biomedical signals include Electrocardiography (ECG), Electroencephalography (EEG), Electromyography (EMG), and Electroretinography (ERG), each operating at different frequency ranges. ECG signals, which have a frequency of approximately 250 Hz, are used to monitor heart activity and detect cardiovascular conditions. EEG signals, with a frequency of 200 Hz, record electrical activity in the brain and are widely used in neurological studies, including epilepsy detection and brain-computer interfaces. EMG signals, operating at 150 Hz, measure muscle activity and help diagnose neuromuscular disorders. ERG signals, with a frequency of 100 Hz, capture electrical responses from the retina and are used in ophthalmology to assess visual function. Understanding these biomedical signals is essential for designing efficient medical devices and diagnostic tools [19].

TABLE I: Most Commonly Used Biomedical Signals

Signal	Frequency
ECG (Electrocardiography)	250 Hz
EEG (Electroencephalography)	200 Hz

EMG (Electromyography)	150 Hz
ERG (Electroretinography)	100 Hz

The Electroencephalogram (EEG) is a method used to record the electrical activity of the brain. It has many applications in both medical diagnosis and brain research. EEG signals can be captured by placing electrodes on the scalp, but the signals are very weak typically in the range of a few microvolts (μV). Due to their low amplitude, these signals must be amplified and processed before they can be digitized using an Analog-to-Digital Converter (ADC) [5].

4. CONCLUSION

This study highlights the critical role of CMOS-based Operational Transconductance Amplifiers (OTAs) in biomedical applications, emphasizing their significance in low-power, low-voltage, and high-linearity designs. The comparative analysis of various OTA architectures demonstrates that modern advancements, such as bulk-driven and current-reuse techniques, contribute significantly to enhancing power efficiency and improving signal processing capabilities. The reviewed literature underscores the growing demand for ultra-low-power OTAs in biomedical signal processing, particularly for applications like ECG, EEG, EMG, and ERG monitoring.

With increasing reliance on battery-powered and implantable medical devices, optimizing OTAs for minimal power consumption while maintaining high gain and low noise is crucial. The findings suggest that ongoing research in this domain should focus on refining transconductance architectures, noise reduction techniques, and adaptive biasing strategies to further enhance energy efficiency and performance. Future developments in OTA design will play a pivotal role in advancing biomedical electronics, ensuring more reliable and efficient medical diagnostic systems.

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