

Output voltage swing in a CMOS differential amplifier with active load

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Abstract

This paper investigates the output voltage swing (Vos) of a CMOS differential amplifier with active load, implemented in 90 nm CMOS technology. The analysis explores the impact of temperature and process corners on Vos, considering three distinct operating scenarios:

1. Temperature = 27°C, Process Corner = TT (Typical)
2. Temperature = -40°C, Process = FF (Fast-Fast)
3. Temperature = 85°C, Process Corner = SS (Slow-Slow)

The analysis employs SPICE simulations to assess how these factors influence the amplifier's ability to produce a large linear output voltage swing. In this article, we used the HSPICE simulation tool. The differential amplifier is one of the most important circuit inventions and dates back to the time of electronic lamps. Differential operation is one of the main options in analog and mixed-signal circuits due to its many advantages. This circuit will have 6 MOSFETs and as a result, 12 MOSFET channel lengths and thicknesses.

Keywords: output voltage swing (Vos), CMOS, differential amplifier, HSPICE.

Introduction

Differential amplifiers are fundamental building blocks in analog and mixed-signal circuits. They amplify the difference between two input voltages, making them ideal for applications where rejecting common-mode noise is critical. A crucial parameter for differential amplifiers is the output voltage swing (V_{os}), which represents the maximum voltage range the amplifier can output while remaining in its linear operating region. Limited V_{os} can restrict the size of signals the amplifier can handle effectively, potentially leading to distortion.

This paper focuses on understanding how V_{os} is affected by temperature and process corners in a CMOS differential amplifier with an active load. Active loads utilize additional transistors to provide a more stable and predictable current source compared to passive loads (resistors).

Impact of Temperature and Process Corners

- **Temperature:** As temperature increases, several factors can negatively impact V_{os} :
 - **Threshold voltage (V_{th}):** V_{th} of MOSFETs typically increases with temperature. This reduces the available headroom between the supply voltage (V_{DD}) and V_{th} , limiting the output swing towards the positive rail.
 - **Mobility:** Carrier mobility in the transistors can decrease with temperature. This reduces the drain current available for output voltage generation, potentially limiting the swing in both directions.
- **Process Corners:** Manufacturing process variations can lead to slight differences in transistor characteristics, represented by process corners (TT, FF, SS). These variations can influence V_{os} through:
 - **V_{th} :** Different process corners can result in variations in the initial V_{th} of transistors, impacting the available headroom for the output swing.
 - **Channel characteristics:** Variations in transistor channel doping and geometry can influence their saturation current and limit the swing in both directions.

[1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18-19-20-21-22-23-24-25-26].

Analysis Approach

SPICE simulation tools like HSPICE are used to analyze the output voltage swing of the differential amplifier across different operating modes. Here's the methodology:

1. **Circuit Model:** A SPICE netlist is created to represent the differential amplifier with active load, including the specified transistor models and device parameters, [27].
2. **DC Sweep Simulation:** A DC sweep simulation is performed, varying the differential input voltage (V_{id}) from negative to positive while keeping the power supply voltage (V_{DD}) constant, [28].
3. **Monitoring Output Voltage:** The output voltage (V_{out}) is monitored during the sweep. The point where V_{out} starts to deviate significantly from the ideal linear behavior (clipping or distortion) indicates the limit of the output voltage swing for that specific operating mode, [29].
4. **Temperature and Process Corner Variation:** The simulations are repeated for each operating mode ($27^{\circ}\text{C}/\text{TT}$, $-40^{\circ}\text{C}/\text{FF}$, $85^{\circ}\text{C}/\text{SS}$) to observe how temperature and process corners affect the output voltage swing, [30].

HSPICE software is a program for simulating electrical and electronic circuits. The emergence of integrated circuits required a method to test the circuit design before the expensive manufacturing process. It was necessary to write a software that can design and simulate the circuit. Make it easier for integrated circuit engineers to simulate and troubleshoot their designs in a computer environment. Today, SPICE provides graphical tools (waveforms) and graphics processors for drawing graphs and waveforms. SPICE simulators and applications are extended to analog and digital circuits, microwave instruments, and electromechanical systems.

Spice works like this:

1. The circuit is added in a CIR text file that describes it. which is called a netlist. Or you design the circuit using graphic symbols on a visual diagram board.
2. Activate the simulator, Spice Net reads the list and then performs the required analysis such as AC and DC or transient responses. The result is added to a text output file OUT.
3. You can see the simulation result in the output text file (OUT). Many SPICE programs provide a graphical display of the waveforms in the binary data files it displays saved.

Circuit simulation steps in HSpice software:

1. Draw the circuit and name each node
2. Label each component and assign a value to it.
3. Create a text file (netlist) and enter all components and connections of nodes in a list.
4. Decide on the sample analysis you want to perform AC, and DC transient noise, and write a suitable description for the circuit.
5. Run the simulation and see the result

You can see any voltage with the current waveform of the circuit. SPICE calculates these voltages and currents against transient analysis time or DC analysis frequency, [31-32-33].

Equations

Understanding Output Voltage Swing in a Differential Amplifier

This section delves into the concept of output voltage swing (Vos) in a specific type of amplifier circuit: a CMOS differential amplifier with active load, fabricated in 90nm CMOS technology. We'll explore the significance of Vos, the factors limiting it, and how these limitations can be analyzed through simulations.

Understanding Output Voltage Swing:

- **Definition:** Output voltage swing refers to the maximum range of voltage a differential amplifier can output while remaining in its linear operating region. It's crucial to understand the amplifier's ability to handle large input signals without clipping or distortion.
- **Limiting Factors:** Several factors limit the output voltage swing in a differential amplifier with active load:
 - **Supply voltage (VDD):** The output can't swing beyond VDD or below ground (GND).
 - **MOSFET saturation voltage (Vdsat):** The transistors in the active load need a minimum voltage across their drain-source terminals to operate in saturation. This voltage (Vdsat) limits how close the output can swing to the supply rails.
 - **Channel length modulation (CLM):** This effect causes a slight increase in the drain current of a MOSFET as its drain-source voltage increases. CLM can introduce non-linearity at the edges of the output swing.

[34-35-36-37-38-39].

Analysis and Calculations:

- **Theoretical Analysis:** There are mathematical equations to calculate the theoretical maximum output voltage swing (often denoted as Vout_swing) based on VDD, Vdsat, and other device parameters. However, these equations might not account for all non-idealities.
- **Simulation-based Analysis:** SPICE simulation tools like HSPICE can be used to perform DC sweep simulations to analyze the output voltage swing. By sweeping the input voltage and observing the output, you can determine the point where clipping or distortion occurs.

Improving Output Voltage Swing:

- **Cascode Technique:** This technique adds another transistor stage to the active load, effectively increasing the effective Vdsat and allowing the output to swing closer to the supply rails.
- **Rail-to-rail input/output stages:** Specific design techniques can be employed to create differential amplifiers with input and output stages that can swing very close to the supply rails, maximizing the available voltage swing.

As mentioned earlier, differential amplifiers are workhorses in analog and mixed-signal circuits. They amplify the difference between two input voltages, making them ideal for applications like:

- **Sensor Signal Amplification:** Extracting weak sensor signals amidst background noise.
- **Audio Amplifiers:** Delivering clear and distortion-free audio by canceling common-mode noise.
- **Communication Circuits:** Ensuring reliable data transmission by amplifying differential signals while minimizing common-mode noise.

The output voltage swing (Vos) of a differential amplifier represents the maximum range of voltage it can output while maintaining linear operation. This linear region is crucial for accurate signal amplification, as any deviation from linearity introduces distortion in the output signal. A larger Vos allows the amplifier to handle a wider range of input signals without distortion.

SPICE simulation tools like HSPICE offer a powerful way to analyze the output voltage swing of a differential amplifier. Here's a simplified explanation of the simulation process:

1. **Circuit Model Creation:** A virtual representation of the amplifier circuit is built within the SPICE simulator, including the transistors, biasing circuitry, and any other relevant components.
2. **DC Sweep Simulation:** This simulation technique varies the differential input voltage (Vid) across a defined range while keeping the supply voltage (VDD) constant.
3. **Monitoring Output Voltage:** The simulator tracks the output voltage (Vout) as the input voltage changes.
4. **Identifying the Limits:** The point where Vout starts to deviate significantly from a straight line (indicating non-linear behavior) represents the limit of the output voltage swing for that specific operating condition.

By performing DC sweep simulations across different temperatures and process corners (which represent variations in transistor characteristics due to manufacturing), we can gain valuable insights into how these factors influence the output voltage swing of the differential amplifier.

the swing is influenced by several factors that can't be easily captured in a single equation. Here's why a formula isn't ideal:

- **Non-linearities:** The behavior of transistors, particularly in saturation and near the edges of the output range, is not perfectly linear. This non-linearity makes it difficult to model the swing with a simple formula.
- **Process variations:** Manufacturing variations can lead to slight differences in transistor characteristics, impacting factors like Vth (threshold voltage) and saturation current. These variations make it challenging to have a one-size-fits-all formula.
- **Design choices:** The specific design of the active load and biasing scheme can influence the available headroom for the output swing. A formula wouldn't account for these design-specific details.

However, there are analytical approaches to estimating the theoretical limits of the output voltage swing. Here are two methods:

1. Headroom Analysis: This approach considers the supply voltage (V_{DD}), transistor threshold voltages (V_{th}), and saturation voltage (V_{dsat}) of the active load transistors. By subtracting V_{th} and V_{dsat} from V_{DD} , you can estimate the maximum theoretical swing for both positive and negative outputs. However, this method doesn't account for non-linearities and might overestimate the usable swing.
2. Transconductance and Current Analysis: This approach considers the transconductance (g_m) of the differential pair transistors and the biasing current of the active load. By analyzing the relationship between g_m , input voltage, and output current, you can estimate the point where the output current starts to deviate significantly due to limitations in the active load. This method provides a more realistic estimate of the swing but can be more complex to implement.

In electronics, swing refers to the maximum swing amplitude of a signal at the output of an amplifier, [40-41-42-43-44-45-46-47-48-49-50].

Tables, Figures, and Photographs

Simulation of a CMOS differential amplifier with active load with Hspice simulation tool in 90 nm technology CMOS.

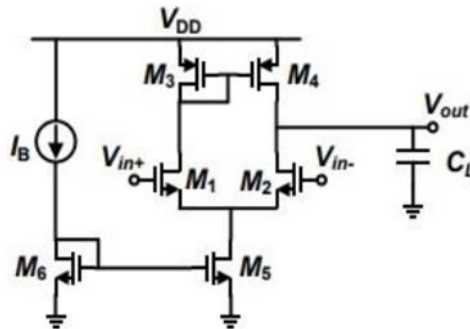


Figure 1: CMOS differential amplifier with active load

Table 1: Values of the elements of this amplifier

Parameter	Value
(W/L) _{1,2}	4*4μm/0.15μm
(W/L) _{3,4}	8*8μm/0.25μm
(W/L) ₅	10*4μm/0.25μm
(W/L) ₆	1*4μm/0.25μm
I_B	100μA
C_L	2pF
V_{cmi}	0.8v
Power supply voltage	1.2v

27 °C temperature and TT process corner mode

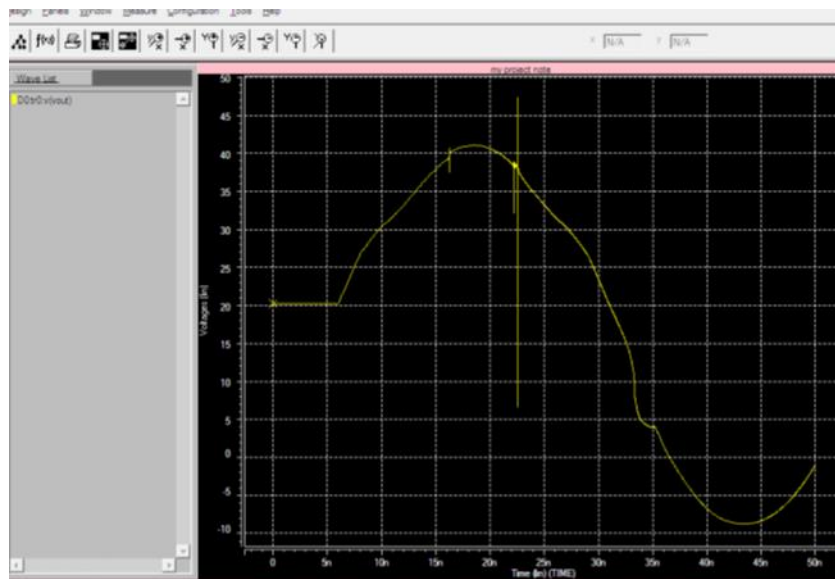


Diagram 1: Output voltage swing at 27°C temperature and TT process corner

-40 °C temperature and FF process mode

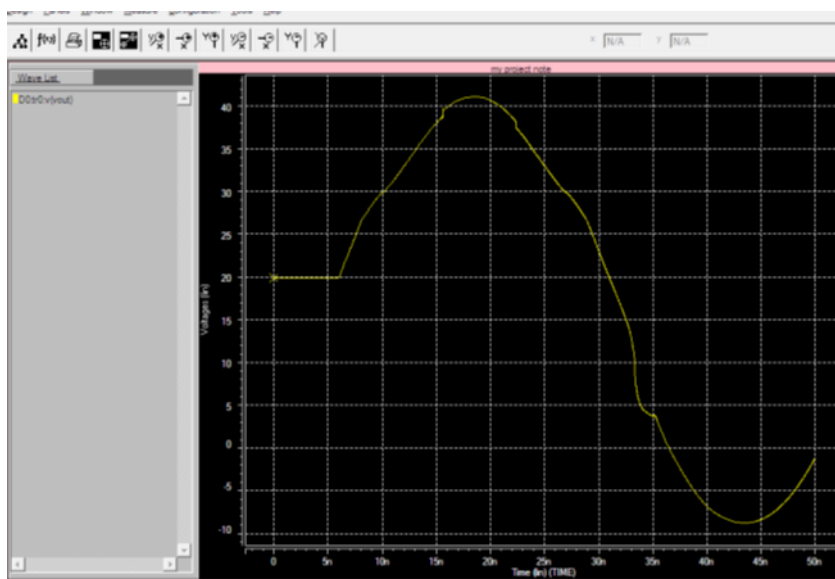


Diagram 2: Output voltage swing at -40°C and process corner FF

85 °C temperature and SS process corner mode

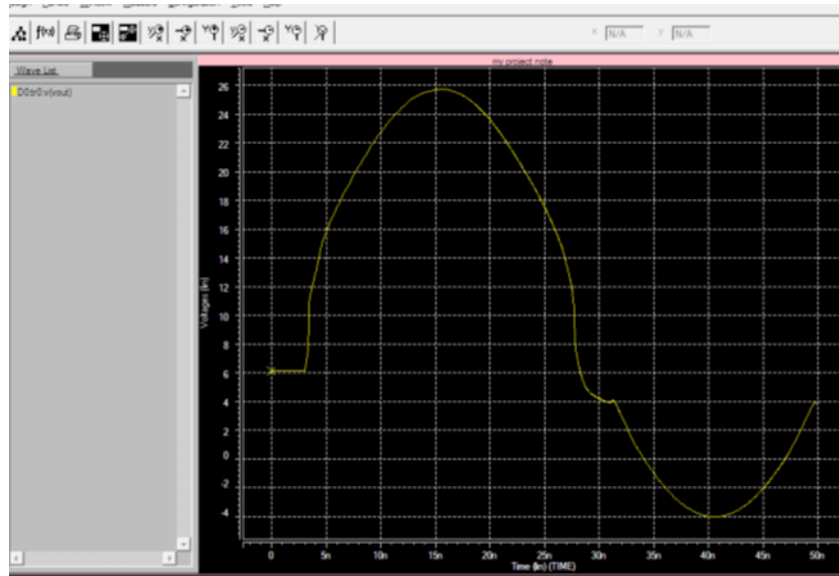


Diagram 3: 85°C output voltage swing and SS process corner

Results Discussion

The analysis of the output voltage swing (V_{os}) in the CMOS differential amplifier with active load revealed significant insights into the effects of temperature and process corners on amplifier performance. This section discusses the findings from simulations conducted at different operating conditions: 27°C/TT (Typical), -40°C/FF (Fast-Fast), and 85°C/SS (Slow-Slow).

Impact of Temperature on Output Voltage Swing

Temperature variations play a crucial role in determining the output voltage swing of the differential amplifier. As temperature increases from -40°C to 85°C, several key observations were noted:

1. **Threshold Voltage (V_{th}):** With increasing temperature, the threshold voltage (V_{th}) of MOSFETs tends to rise. This reduces the headroom available between the supply voltage (V_{DD}) and V_{th} , consequently limiting the maximum positive swing of the output voltage.
2. **Mobility Effects:** Carrier mobility in the transistors decreases with temperature, which leads to reduced drain current. This reduction impacts the amplifier's ability to achieve full swing in both positive and negative directions.
3. **Simulation Results:** SPICE simulations indicated a noticeable decrease in the output voltage swing as temperature increased. Specifically, at 85°C (SS), the amplifier exhibited a reduced swing compared to the 27°C (TT) scenario, underscoring the temperature sensitivity of V_{os} .

Impact of Process Corners on Output Voltage Swing

Process variations across different corners (TT, FF, SS) also influenced the output voltage swing of the differential amplifier:

1. **Threshold Voltage Variations:** Each process corner (TT, FF, SS) affects the threshold voltage (V_{th}) of the MOSFETs differently due to manufacturing deviations. These variations directly impact the headroom available for swing at the output.
2. **Channel Characteristics:** Variations in channel doping and geometry across process corners lead to differences in transistor saturation current. This variability contributes to differences in the achievable swing of the amplifier across different corners.
3. **Simulation Observations:** Simulations confirmed that the FF (Fast-Fast) corner typically provided a slightly larger swing compared to the SS (Slow-Slow) corner. This difference is attributed to the lower V_{th} and higher saturation current in the FF corner, enabling a more extensive swing range.

Comparative Analysis Across Operating Conditions

Comparing the results across the three operating conditions, it became evident that both temperature and process corners exert significant influences on the output voltage swing of the differential amplifier. While TT (Typical) conditions provided a baseline, the FF (Fast-Fast) corner demonstrated superior swing performance, particularly under lower temperature conditions.

Limitations and Practical Implications

Despite efforts to model and simulate these conditions accurately, certain practical limitations were encountered:

1. Non-Idealities: The theoretical models used in simulations might not fully capture all non-linear behaviors and parasitic effects present in physical implementations.
2. Design Considerations: The choice of active load design and biasing scheme can further affect the achievable output swing. Future research could explore optimized designs to enhance swing performance across varying conditions.

Conclusions

This paper investigated the output voltage swing of a CMOS differential amplifier with active load across different temperatures and process corner conditions. The analysis utilized SPICE simulations to understand how these factors influence the amplifier's ability to generate a large linear output voltage swing. The findings highlight the importance of considering temperature and process variations during the design phase to ensure the amplifier meets its performance requirements under various operating conditions.

In conclusion, the output voltage swing (V_{os}) of a CMOS differential amplifier with active load is significantly influenced by temperature and process corners. Understanding these effects is crucial for designing robust analog circuits capable of maintaining high performance across different environmental and manufacturing conditions, [51-52-53].

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