A CMOS Single-Supply Op-Amp Design For Hearing Aid Application

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Abstract: The hearing aids specific operational amplifier described in this paper is a single-supply, low voltage CMOS amplifier. It works on 1.3V single-supply and gets a gain of 82dB. The 0.18 μm CMOS process was chosen to reduce the driven voltage as well as the power dissipation.

Keywords: CMOS Operational Amplifier, Low-voltage, Single-supply

1. INTRODUCTION

Operational amplifiers are the basic building blocks in both analog and mixed-signal circuits. The operational amplifiers used in hearing aids are specially designed to meet the requirements of low voltage, single-supply, low power dissipation, high gain, etc. Because the input signal from microphone is very small, less than 1mV, the op-amp is designed to be very sensitive to such a tiny signal. On the other hand, the op-amp should have a rail-to-rain output swing as well as a very low output impedance to avoid distortion and waste of power.

2. OPERATIONAL AMPLIFIER

The op-amp consists of three stage, input stage, gain stage and output stage. The input stage is an N-channel differential pair. The gain stage is a current load common source P-channel transistor. A class AB push pull stage acted as the output buffer to deal with a small resistor load.

2.1 Input Stage

The input signal is less than 0.01mV. That is,

\[ V_{c} - 0.01mV \leq V_{c}' \leq V_{c} + 0.01mV \]  \quad (1)

\[ V_{in} = V_{DSAT5} + V_{DSAT4} - V_{TN} \]  \quad (2)

\[ V_{in} = V_{DD} - V_{DSAT4} - V_{TN} \]  \quad (3)

Where \( V_{DSAT5} \) and \( V_{DSAT4} \) are the saturation voltage of transistors M5 and M4 and M1. \( V_{TN} \) is the threshold voltage of N channel transistor. So in the design, we do not need to take cascode in input stage to extend the common mode input range (ICMR). A regular N-channel differential pair input stage provides enough ICMR for the op-amp. We chose a carrier, \( V_c = 0.7V \). Fig 2 shows the transistor level schematic. Transistors Mb1, Mb2 and the resistor \( R_{ref} \) compose a voltage divider to provide the carrier for the circuit. Node 6 is the output to the next stage. \( V_{signal} \) is the input signal.

\[ A_{dm} = \frac{V_{od}}{V_{id}} = -g_{m}(R_{D} / r_{od}) \]  \quad (4)

Equation (4) state the relationship among circuit parameters, where \( V_{od} \) is the differential mode output voltage and \( V_{id} \) is the differential mode input voltage. \( g_{m} \) is the transconductance of transistor M2, M1. \( R_{D} \) is the equivalent load resistance. To improve the gain, we
may increase the gate length of the M1 and M2, the ratio of W/L or reduce the current from current source Ib1.

<table>
<thead>
<tr>
<th>Transistor</th>
<th>W [μm]</th>
<th>L [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>16.30</td>
<td>1.00</td>
</tr>
<tr>
<td>M2</td>
<td>16.30</td>
<td>1.00</td>
</tr>
<tr>
<td>M3</td>
<td>23.74</td>
<td>1.00</td>
</tr>
<tr>
<td>M4</td>
<td>23.74</td>
<td>1.00</td>
</tr>
<tr>
<td>M5</td>
<td>10.63</td>
<td>1.00</td>
</tr>
<tr>
<td>M6</td>
<td>10.63</td>
<td>1.00</td>
</tr>
<tr>
<td>M7</td>
<td>10.21</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 2 shows the small signal transfer characteristics of the gain stage. It got a gain of 92.78 at low frequency.

Table 2 small-signal transfer characteristics

<table>
<thead>
<tr>
<th>Vout/Vin</th>
<th>92.78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Resistance</td>
<td>1.000e+20</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>466.102k</td>
</tr>
</tbody>
</table>

The gain stage used in the design is a regular active load common source amplifier. M11, M10, Ref2 and M9 compose a current source. The diode connection transistor M11 could be regarded as a large resistor so that we can reduce the size of the resistor, Ref. M10 is exactly the same as M9 so that the current through M11 equals to the current through the transistor M8. Vinput is the output from input stage. The hearing aids are only interested in the low frequency input signals which covers between 20 Hz and 8kHz. We found there is no phase shift when the input frequency is less then 10E4 Hz even we did not do any frequency compensation. Fig. 5 shows the structure of the gain stage.

2.2 Gain Stage

The gain of active load common source transistor is determined by the transconductance of the transistor M8 and the equivalent load resistance. Equation. (4). So we can increase the gate length, the W/L to get a larger gain. Reduce current also help to do so. Fig. 6 show the frequency response of the gain stage.

2.3 Output Stage

The desired gain of the op-amp is 80dB. The input signal is
less than 0.01 mV. The output is

\[ V_{oc} - 100 mV \leq V_{OUT} \leq V_{oc} + 100 mV \]

So a source follower was chosen to be the output stage. (Fig. 7)

Fig. 7 Transistor Level Schematic of Output Stage

Fig. 8 (a) DC Transfer Characteristic

Fig. 9 The Full Schematic of the Op-amp

Table 3 Small-Signal Transfer Characteristics

<table>
<thead>
<tr>
<th>Vout/Vin</th>
<th>978.2 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Resistance</td>
<td>1.000e+20</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>28.23 kΩ</td>
</tr>
</tbody>
</table>

3. FULL CIRCUIT SIMULATION AND TEST

Fig. 9 shows the full schematic of the op-amp. In this schematic, the voltage divider which produce the carrier was not included. The transistors M7, M6, M5 and resistor Rref compose a current source. M1, M2, M3, M4 and M5 consist a N-Channel differential pair. M5 provided a tail current. The transistor M8 is a common source amplifier with a current source load. The transistor M10 is a source follower. All these parts are analyzed and simulated on former section. Here we tested the specifications of the op-amp.

The specifications we interested in are gain, phase margin, ICMR, Common Mode Reject rang (PRSS), output swing, Common Mode Rejection Range (CMRR) and Settling time.

3.1 Frequency response

Table 4 and Fig. 10 show frequency response of op-amp. The gain is 82 dB. There is enough phase margin to deal with low frequency with acceptable phase shift.

Table 4 Small-Signal Transfer Characteristics

<table>
<thead>
<tr>
<th>Vout/Vin</th>
<th>12.25 kΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Resistance</td>
<td>1.000e+20</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>25.04 kΩ</td>
</tr>
</tbody>
</table>

Fig. 10 (a) Amplitude-Frequency Response
3.2 CMRR

CMRR, Common Mode Reject Range, is defined as Equation (5). The \( A_{CM} \) is common-mode gain and the \( A_{DM} \) is the differential-mode gain. In fig. 11(a), we use the absolute value.

\[
CMRR = \frac{A_{CM}}{A_{DM}}
\]  

(5)

3.3 Output Swing

The output is between 0V and 767mV when the input varies in the ICMR.

3.4 PSRR

PSRR, Power-Supply Rejection Ratio. Assume that the chip ground is reliable. The test only on the supply. It turned out to be 125dB at 0dB.

3.5 Settling Time

We added a tiny pulse on input. The Settling time is:
- Settling Time+ = 31ns;
- Settling Time- = 73ns.
### Table 5 Specifications.

<table>
<thead>
<tr>
<th>Spec</th>
<th>Designed Value</th>
<th>Simulation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>80dB</td>
<td>82.47dB</td>
</tr>
<tr>
<td>Settling time +</td>
<td></td>
<td>31 ns</td>
</tr>
<tr>
<td>Settling time -</td>
<td></td>
<td>73 ns</td>
</tr>
<tr>
<td>ICMR +</td>
<td>710mV</td>
<td>710mV</td>
</tr>
<tr>
<td>ICMR -</td>
<td>690mV</td>
<td>690mV</td>
</tr>
<tr>
<td>CMRR</td>
<td>50dB</td>
<td>85dB</td>
</tr>
<tr>
<td>PSRR+</td>
<td>60dB</td>
<td>125.7dB</td>
</tr>
<tr>
<td>Output Swing+</td>
<td>750mV</td>
<td>767V</td>
</tr>
<tr>
<td>Output Swing</td>
<td>0V</td>
<td>0V</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>As small as possible</td>
<td>12.3k</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>Infinite</td>
<td>1.0e20</td>
</tr>
<tr>
<td>Total Power</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4. CONCLUSION

A low voltage single-supply operational amplifier for hearing aids application was designed in this paper. By using short channel devices, it works on a 1.3V single supply and get a gain of 82dB. The analog circuit involved in hearing aids design contributes a lot to the high performance of the chip. We will further our research on this area.

### ACKNOWLEDGMENTS

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### REFERENCES


### Appendix I.

**SPICE CODING**

1) Differential Pair

```plaintext
****N channel differential pair:**** .lib /usr/COMLIB/L18.lib’ nn .option post = 2 vdd 4 0 1.3 vin 1 0 sin(.7 .01m 1000 0 0 ) vinp 2 0 .7
```

2) Gain Stage

```plaintext
******* Gain stage *************** .lib /usr/COMLIB/ L18.lib’ nn .option post = 2 vdd 4 0 1.3 ib 10 0 25u vin 1 0 sin(.75 .1s 1000 0 0) * Input signal .para lm = 1u M1 9 10 4 4 pch w = 46.78u l = lm as = 55.2f ad = 55.2f ps = 49.14u pd = 49.14u M2 9 1 0 0 nch w =10.91u l = lm as = 12.9f ad = 12.9f ps = 13.27u pd = 13.27u M3 10 10 4 4 pch w = 13.56u l = lm as = 18.1f ad = 18.1f ps = 15.92u pd = 15.92u .op .tf v(9) vin .tran .01m 5m .print tran v(9) .end
```

3) Output Stage

```plaintext
**** N-channel Source Follower with Bias.**** .lib /usr/COMLIB/L18.lib’ nn .option post = 2 vdd 4 0 1.3 vin 1 0 sin(.9 .1 1000 0 0) * Input signal * vin 1 0 dc = .7 m1 4 1 2 2 nch w=.42u l = .18u as = 0.15f ad = 0.1 5f ps = 1.14u pd = 1.14u
```
4) Full Operational Amplifier

*** The Full operational amplifier ************
.lib /usr/COMLIB/L18.lib
.option post = 2

vdd 4 0 1.3
*vinn 1 0 sin(.7 .01m 1000 0 0 )
vinn 2 0 dc = .7 ac = 0.01m
vinp 1 0 .7
rref1 7 8 10k
rref2 4 11 80k
m1 3 1 5 5 nch w = 16.00u l = 1u as = 21.76f ad = 2
1.76f ps = 18.72u pd = 18.72u
m2 6 2 5 5 nch w = 16.00u l = 1u as = 21.76f ad = 2
1.76f ps = 18.72u pd = 18.72u
m3 3 3 4 4 pch w = 23.70u l = 1u as = 32.23f ad = 3
2.23f ps = 26.42u pd = 26.42u
m4 6 3 4 4 pch w = 23.70u l = 1u as = 32.23f ad = 3
2.23f ps = 26.42u pd = 26.42u
m5 5 7 0 0 nch w = 10.63u l = 1u as = 14.46f ad = 1
4.46f ps = 13.35u pd = 13.35u
m6 7 7 0 0 nch w = 10.63u l = 1u as = 14.46f ad = 1
4.46f ps = 13.35u pd = 13.35u
m7 8 8 4 4 pch w = 10.87u l = 1u as = 14.78f ad = 1
4.78f ps = 13.59u pd = 13.59u

m8 9 6 4 4 pch w = 47.31u l = 1u as = 55.2f ad = 55.
2f ps = 49.14u pd = 49.14u
m9 9 7 0 0 nch w = 10.63u l = 1u as = 12.9f ad = 12.
9f ps = 13.27u pd = 13.27u

m10 4 9 10 10 nch w = .42u l = .18u as = 0.15f ad =
0.15f ps = 1.14u pd = 1.14u
m11 10 12 0 0 nch w = .22u l = .18u as = 0.08f ad =
0.08f ps = 0.58u pd = 0.58u
m12 11 11 12 12 nch w = .22u l = .18u as = 0.08f ad =