Advanced BJT Op-Amps

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5234 predecessor Op-Amp

complementary input stage with current control and summing circuit

intermediate stage

class-AB control

push and pull Darlington output transistors
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Input Stage

• The input stage is similar to MOS design.
• Take a pnp input stage (Q1-Q2) with npn current mirror load (Q3-Q4) and a pnp tail current source (Q5).
• Then,
  \[ V_{IC(\text{max})} = V_{CC} - |V_{BE1}| - |V_{CE5(sat)}| \]
  \[ V_{IC(\text{min})} = -V_{EE} + V_{BE3} - |V_{BE1}| + |V_{CE1(sat)}| \]
Input Stage

- If it is desired to bring the minimum input common mode voltage to ground, the current mirror can be replaced by resistors.
- In this case, gain will be low.
- To improve this situation, a folded cascode stage can be used.
Input Stage
Input Stage

• With this configuration,

\[ \frac{v_{od}}{v_{id}} = g_{m1} \rho_1 R_{o1} \]

\[ \rho_1 = \frac{R_3}{R_3 + r_{e3}} \]

\[ R_{o1} \approx \left[ r_{06} \left(1 + g_{m6} R_6 \right) \right] \left[ r_{03} \left(1 + g_{m3} R_3 \right) \right] \]

• The assumption here is that \( g_{m6} R_6 \ll \beta_{pnp} \) and \( g_{m3} R_3 \ll \beta_{nnp} \).

• For rail to rail operation, add another stage.
Input Stage
Input Stage

[Diagram with transistor symbols and resistors labeled]

Vin- → Q1 → Q2 → Vin+ → Q5

R6

Q8 → Q9 → Q10

VCC

R8

R9

R7

-VEE=0

+ Vod -
Input Stage

- This stage has rail to rail operation for a supply of 2V or more.
- However, it suffers from the problem of non-constant $g_m$ discussed earlier.
- This variation of $g_m$ causes a variation in open-loop gain and frequency response of the OPAMP, compromising its performance when designed to be stable in closed loop configuration.
**DESCRIPTION**
The NE/SA5234 is a matched, low voltage, high performance quad operational amplifier. Among its unique input and output characteristics is the capability for both input and output rail-to-rail operation, particularly critical in low voltage applications. The output swings to less than 50 mV of both rails across the entire power supply range. The NE/SA5234 is capable of delivering 5.5 V peak-to-peak across a 600 Q load and will typically draw only 700 µA per amplifier. The bandwidth is 2.5 MHz and the 1% settling time is 1.4 µs.

**FEATURES**
- Wide common-mode input voltage range: 250 mV beyond both rails
- Output swing within 50 mV of both rails
- Functionality to 1.8 V typical
- Low current consumption: 700 µA per amplifier
- ±35 mA output current capability
- Unity gain bandwidth: 2.5 MHz
- Slew rate: 0.8 V/µs
- Low noise: 25 nV/√Hz
- Electrostatic discharge protection
- Short-circuit protection
- Output inversion prevention

**APPLICATIONS**
- Automotive electronics
- Signal conditioning and sensing amplification
- Portable instrumentation
  - Test and measurement
  - Medical monitors and diagnostics
  - Remote meters
- Audio equipment
- Security systems
- Communications
  - Pagers
  - Cellular telephone
  - LAN
  - 5 V Datacom bus
- Error amplifier in motor drives
- Transducer buffer amplifier

**ORDERING INFORMATION**

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<td>0 °C to +70 °C</td>
<td>NES234D</td>
<td>SOT18-1</td>
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Matched quad high-performance low-voltage operational amplifier

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NE5234 biasing circuit

Figure 6.34 Schematic of the NE5234 bias circuit.
Figure 6.34 Schematic of the NE5234 bias circuit.
NE5234 Biasing Circuit

- Q49, Q60, and R60 form a Widlar Current Mirror.
- The bases of Q49 and Q60 are driven by a unity-gain buffer (Q50-Q53) to follow the collector of Q49.
- This is simply a beta-helper to reduce the beta error.
- Here, a complementary emitter follower is utilized instead of using a single transistor to reduce the supply voltage.
NE5234 Biasing Circuit

• Similarly, Q54-Q57 act to bias the bases of Q47 and Q58.

• Finally, Q48 and Q59 are just cascode transistors to reduce the dependence of currents on $V_{CC}$.

• To concentrate on the core of the circuit, let us remove the beta helpers and cascodes.
NE5234 biasing circuit
NE5234 Biasing Circuit

• This is just a self-biased current source using thermal voltage as we studied earlier.
• The emitter area of Q60 is twice the area of Q49.
• The current can easily be calculated as

\[ |I_{C47}| = I_{C49} = |I_{C58}| = I_{C60} = \frac{V_T}{R_{60}} \ln 2 = 6 \mu A \]
NE5234 Biasing Circuit

- If R60 is constant, these currents are proportional to absolute temperature (PTAT).
- Resistor R57 is used to prevent zero current through the circuit.
NE5234 input stage

Figure 6.36 Simplified schematic of the NE5234 input stage.
NE5234 input stage

Normally off except when input common mode is less than 0.8 v

Figure 6.36 Simplified schematic of the NE5234 input stage.
NE5234 Input Stage

• Node Bias1 comes from the previous bias circuit.
• Thus, $I_{C11}$ is 6μA, $I_{C12}$ 3μA, and $I_{C13}$, $I_{C14}$ 6μA.
• $I_{C12}$ flows into Q8 and R8, setting the voltage from the base of Q5 to ground to approx. 0.8V.
• If the common mode input is much less than 0.8V, the current of Q11 flows through Q3-Q4, turning OFF Q5, Q7, Q6, and thus Q1-Q2.
NE5234 Input Stage

- If the input common mode signal is much larger than 0.8V, the current of Q11 flows through Q5-Q7 and thus Q1-Q2, turning Q3-Q4 OFF.

- If the input common-mode voltage is around 0.8V, the current of Q11 is split between Q1-Q2 pair and Q3-Q4 pair. Thus, the total transconductance remains the same.
Figure 6.36 Simplified schematic of the NE5234 input stage.
NE5234 input stage

Figure 6.36 Simplified schematic of the NE5234 input stage.
NE5234 Input Stage

- Q9-Q10 and Q13-Q14 operate in the active mode with 6μA of current.
- However, the output of the first stage is very sensitive to matching.
- Thus, a CM signal is created in the second stage and fed back to the bases of Q9 and Q10.
Switching between two transconductors vs. input C-Mode
Figure 6.37 Schematic of the NE5234 second stage. Node Out is the output of the third stage (shown in Fig. 6.39).
NE5234 Second Stage

- Nodes 9 and 10 are coming from the first stage.
- C21 and C22 are for frequency compensation.
- Q21 and Q22 are for buffering so that the second stage does not load the first one.
- Ignore Q23 and Q24 as they are normally OFF.
- Transistors Q25-Q28 form a differential pair.
NE5234 Second Stage

- $I_{C15} = 3 \mu A$, $I_{C16} = I_{C19} = 4 \mu A$, $I_{C17} = I_{C18} = 21 \mu A$, and $I_{C20} = 6.6 \mu A$.
- The current $I_{C15}$ flows through the Schottky diode D1 and creates a voltage drop of 0.4V.
- Q29, R29, and Q30 form a Widlar Current Mirror.
- Q29 is 7 times larger than Q30, giving $I_{C29}$ as 42 $\mu A$. 
NE5234 Second Stage

- Using this value, the current of the differential pair is \(42\mu A - 3\mu A = 39\mu A\).
- Therefore, the individual currents of the four differential pair transistors are around \(10\mu A\).
- Define \(V_{cmout1} = \frac{1}{2}(V_9 + V_{10})\)
- For the first stage, \(V_{cmout1}\) is an output and \(V_{biascm}\) is an input.
NE5234 Second Stage

- For small values of $V_{\text{biascm}}$, the transistors Q9 and Q10 are off and $V_{\text{cmout1}}$ is approx. $V_{\text{CC}} - 0.3$.
- For large values of $V_{\text{biascm}}$, $V_{\text{cmout1}}$ drops to about 0.3V.
- The threshold is around 0.9V.
- Please see your book for details.
- For the second stage, $V_{\text{biascm}}$ is an output and $V_{\text{cmout1}}$ is an input.
NE5234 Second Stage

• In this case, $V_{\text{biascm}} = V_{\text{cmout1}} + 0.4V$
• The solution to these two characteristics is when $V_{\text{biascm}} = 0.9V$ and $V_{\text{cmout1}} = 0.4V$.
• This structure is also an example of CMFB.
NE5234 Output stage

Figure 6.39 Schematic of the NE5234 output stage.
NE5234 Output stage

Figure 6.39 Schematic of the NE5234 output stage.
NE5234 Output Stage

- The NE5234 does not use an emitter follower configuration for the output due to the low supply voltage limitations.
- Nodes 25 and 26 are the inputs coming from the second stage.
- Capacitors C25 and C26 as well as resistors R25 and R26 are for frequency compensation.
- The output is driven by Q74 and Q75.
NE5234 Output Stage

- The high current drive requirement for the output transistors result in high base currents.
- The base of Q75 is driven by an emitter follower Q68.
- The base of Q74 also has to be driven. However, the $\beta$ of pnp transistors are lower. Thus, a complementary pair Q64-Q65 is used.
NE5234 Output stage

Figure 6.39 Schematic of the NE5234 output stage.
NE5234 Output stage

![Schematic of the NE5234 output stage](image)

Figure 6.39 Schematic of the NE5234 output stage.
NE5234 Output Stage

- The voltages Bias1 and Bias5 are coming from the bias circuit discussed earlier.
- They set $I_{C61}$ to 6μA and $I_{C63}$ and $I_{C64}$ to 33μA.
- Transistors Q70, Q72, and Q73 are normally OFF.
- All other biasing is set by the output bias circuit.
- PBASE and NBASE are set by the output stage and are inputs to the output bias circuit.
- The next slide shows a simplified diagram of the output bias circuit and the output stage together.
NE5234 output stage with simplified biasing

Figure 6.41 Simplified schematic of the NE5234 output stage with its bias circuit.
NE5234 output stage with simplified biasing

Figure 6.41 Simplified schematic of the NE5234 output stage with its bias circuit.
NE5234 Output Stage

- In this diagram, transistors which are normally OFF are omitted and some current mirrors are shown as ideal current sources.
- In classical class AB common collector output stages, the product of currents is a constant.
- In theory, these transistors never turn off.
- However, due to voltage drops in the base and emitter resistances, they do turn off.
- This causes extra delays, worsening the crossover distortion even further.
NE5234 Output Stage

• In the NE5234, the transistors can never turn OFF.
• The collector currents of the output transistors are observed by observing the base-emitter voltages.
• These voltages are eventually sent to Q45-Q46 for comparison.
NE5234 Output Stage

• This can be written analytically as,

\[ V_{B46} = V_{BE75} = V_T \ln \left( \frac{I_{C75}}{I_{S75}} \right) \]

\[ V_{B45} = V_{BE42} + \left| I_{C43} \right| R_{42} \]

\[ \left| I_{C43} \right| = \frac{V_{EB74} - V_{EB43}}{R_{43}} \]

• Assuming \( R_{42} = R_{43} \),

\[ V_{B45} = V_{BE42} + V_{EB74} - V_{EB43} = V_{EB74} + V_T \ln \left( \frac{I_{S43}}{I_{S42}} \right) \]
NE5234 Output Stage

- This yields \( V_{B45} = V_T \ln \left( \frac{|I_{C74}|}{I_{S75}} \right) \) if \( I_{S75} = \frac{|I_{S74}|I_{S42}}{|I_{S43}|} \)

- If the difference between \( V_{B45} \) and \( V_{B46} \) exceeds \( 3V_T \) in either direction, the transistor with the higher base voltage turns OFF.

- Then, the emitter voltage is controlled by the other transistor.

- This is the input to Q40 of the other differential pair.
NE5234 Output Stage

• The other side is a constant voltage created by $I_{\text{REF}}$ across the two diode connected transistors Q37 and Q38.

• This forms a feedback loop.

• Assume that Q75 conducts a large current to pull the OPAMP output low.

• Now assume that the voltage at the base of Q40 rises.
NE5234 Output Stage

- Then, $I_{C40}$ is increased and $I_{C39}$ is reduced. Then, the node voltage of 25 is increased, thus increasing the voltage on Pbase.
- This change reduces $V_{B45}$ and hence $V_{B40}$.
- This is opposite to what happened initially.
- In normal operation, $V_{B39}$ and $V_{B40}$ are about equal.
NE5234 Output Stage

• Now, let us outline the analytical calculation.

\[ |I_{C45}| + |I_{C46}| = |I_{C44}| \]

\[ V_{BE75} + V_{EB46} - V_{EB45} - V_{B45} = 0 \]

\[ V_{BE75} + V_{EB46} - V_{BE40} - I_{40}R_{40} + I_{39}R_{39} + V_{BE39} - V_{BE37} - V_{EB38} = 0 \]

• Using the concept of feedback to equalize the base voltages of Q39 and Q40,

\[ V_{BE40} + I_{R40}R_{40} = V_{BE39} + I_{R39}R_{39} \]

\[ V_{BE75} + V_{EB46} - V_{BE37} - V_{EB38} = 0 \]

\[ V_T \ln \left( \frac{I_{C75}}{I_{S75}} \right) + V_T \ln \left( \frac{I_{C46}}{I_{S46}} \right) - V_T \ln \left( \frac{I_{C37}}{I_{S37}} \right) - V_T \ln \left( \frac{I_{C38}}{I_{S38}} \right) = 0 \]
NE5234 Output Stage

- Setting $I_{C37} = |I_{C38}| = I_{REF} = |I_{C36}| - I_{C35}$,

\[
\left(\frac{I_{C75}}{I_{REF}}\right) \frac{I_{S37}}{I_{S75}} = \left(\frac{I_{REF}}{I_{C46}}\right) \frac{I_{S46}}{I_{S38}}
\]

- Also, from the previous equations,

\[
V_T \ln\left(\frac{I_{C75}}{I_{S75}}\right) + V_T \ln\left(\frac{I_{C46}}{I_{S46}}\right) - V_T \ln\left(\frac{I_{C45}}{I_{S45}}\right) - V_T \ln\left(\frac{I_{C74}}{I_{S75}}\right) = 0
\]

- Assuming Q45 and Q46 are identical,

\[
\frac{I_{C75}}{I_{C74}} = \frac{I_{C45}}{I_{C46}} = \frac{I_{C44} - I_{C46}}{I_{C46}}
\]
NE5234 Output Stage

- Solving for $I_{C46}$ and substituting it to one of the earlier equations yields,

$$\left| I_{C46} \right| = \frac{\left| I_{C44} \right| \left| I_{C74} \right|}{I_{C75} + \left| I_{C74} \right|}$$

$$\frac{I_{C75} \left| I_{C74} \right|}{I_{C75} + \left| I_{C74} \right|} = \frac{I_{REF}^2}{I_{C44} \left| I_{S75} \right| \left| I_{S46} \right|}$$

- In the NE5234, $I_{REF} = 7.4\mu A$, $\left| I_{C44} \right| = 6\mu A$, $I_{S75}/I_{S37} = 10$, and $\left| I_{S46} \right| / \left| I_{S38} \right| = 2$. 
NE5234 Output Stage

- When the load current is zero, both currents are equal at about $360\mu\text{A}$.
- When one current goes to infinity, the other saturates at around $180\mu\text{A}$.
- Now, you can calculate all other currents.
NE5234 Small Signal Analysis

- Let us break the circuit into three stages, input stage, second stage, and output stage.
- $\beta_{nnp} = 40, \beta_{pnp} = 10, V_{A,nnp} = 30V, \text{ and } V_{A,pnp} = 20V.$
- The input stage is a fully differential circuit with two pairs and the input resistance depends on which of the two are conducting.
- Assume $V_{IC} << 0.8V$. Q1-Q2 is OFF, Q11 biases the pnp pair Q3-Q4.
Overall small signal analysis model

Figure 7.36 An ac schematic of the high-frequency gain path of the NE5234 assuming that $V_{ic}$ is low enough that $Q_1$ and $Q_2$ in Fig. 6.36 are off.
NE5234 Small Signal Analysis
NE5234 Small Signal Analysis

- From this figure,

\[ R_{id} = 2r_{\pi 3} = 170 \, k\Omega \]

\[ R_{up1} = \frac{r_{013} + R_{13} \left( 1 + \frac{g_{m13} r_{013} (\beta_{pnp} + 1)}{\beta_{pnp}} \right)}{1 + \frac{g_{m13} R_{13}}{g_{m13} r_{\pi 13}}} \approx \frac{r_{013} \left( 1 + g_{m13} R_{13} \frac{\beta_{pnp} + 1}{\beta_{pnp}} \right)}{1 + \frac{g_{m13} R_{13}}{\beta_{pnp}}} = 18 \, M\Omega \]

- Similarly,

\[ R_{down1} \approx \frac{r_{09} \left( 1 + g_{m9} R_9 \frac{\beta_{npn} + 1}{\beta_{npn}} \right)}{1 + \frac{g_{m9} R_9}{\beta_{npn}}} \approx \frac{r_{09} \left( 1 + g_{m9} R_9 \right)}{1 + \frac{g_{m9} R_9}{\beta_{npn}}} = 27 \, M\Omega \]
NE5234 Small Signal Analysis

• Then, the overall output impedance is

\[ R_{o1} = R_{up1} \parallel R_{down1} = 11M\Omega \]

• The transconductance of the input stage is,

\[ G_{m1} = g_{m3}\rho_3 \]

\[ \rho_3 \approx \frac{R_9}{R_9 + r_e} = 0.84 \]

\[ G_{m1} = 97 \mu S \]
NE5234 Small Signal Analysis

- The input resistance of the second stage is given by,

\[ R_{i2} = 2 \left[ r_{\pi 21} + (\beta_{pnp} + 1)(r_{\pi 25} \parallel r_{\pi 26}) \right] = 1.3 \, M\Omega \]

- To find the output resistance, we again divide the resistance into two parallel branches.

\[ R_{up2} = \frac{r_{017} + R_{17} \left(1 + \frac{g_{m17} r_{017} (\beta_{pnp} + 1)}{\beta_{pnp}}\right)}{1 + \frac{g_{m17} R_{17}}{g_{m17} r_{\pi 17}}} \approx \frac{r_{017} \left(1 + g_{m17} R_{17} \frac{\beta_{pnp} + 1}{\beta_{pnp}}\right)}{1 + \frac{g_{m17} R_{17}}{\beta_{pnp}}} = 5.0 \, M\Omega \]
NE5234 Small Signal Analysis

- Looking down into the collector of Q25 or Q26,

\[ R_{down2} = r_{025} \left( 1 + g_{m25} R_{E25} \right) \]

\[ R_{E25} = r_{e26} + \left( \frac{\beta_{npn}}{\beta_{npn} + 1} \right) \left( \frac{R_{up2} \cdot R_{in3(26)}}{g_{m26} r_{026}} \right) \left\| r_{e27} \right\| r_{e28} \]

\[ R_{E25} \approx \left( \frac{\beta_{npn}}{\beta_{npn} + 1} \right) \left[ \frac{1}{g_{m26}} \left\| \frac{1}{g_{m27}} \right\| \frac{1}{g_{m28}} \right] = 0.85 \text{ kΩ} \]

\[ R_{down2} = 4.0 \text{ MΩ} \]

- Combining these, \( R_{o2} = R_{up2} \left\| R_{down2} = 2.2 \text{ MΩ} \right\)
NE5234 Small Signal Analysis
NE5234 Small Signal Analysis

- $a_{v21}$ and $a_{v22}$ represent the small-signal gains of the emitter followers Q21 and Q22.
- Each emitter follower drives a load of $R_L$ where

$$R_L = r_{\pi 25} \| r_{\pi 26} = r_{\pi 27} \| r_{\pi 28} = r_{\pi 25}/2$$

$$a_{v21} = a_{v22} = \frac{1}{1 + \frac{r_{\pi 21}}{(\beta_{pnp} + 1)[(r_{\pi 25}/2) \| r_{021}]}} = 0.90$$

- The transconductance of the second stage can be defined as

$$G_{m2} = \frac{i_o}{v_9 - v_{10}} \bigg|_{v_{25} = 0}$$
NE5234 Small Signal Analysis

• Instead of using a differential voltage $v_9 - v_{10}$ at the input, assume that $v_{10}$ is zero and redefine $G_{m2}$ as

$$G_{m2} = \left. \frac{i_o}{v_9} \right|_{v_{25}=0}$$

• Use superposition to find $i_o$ such that

$$i_{o1} = \frac{g_{m25}}{1 + g_{m25}R_{E25}} a_{v21} v_9$$
NE5234 Small Signal Analysis

- To find the second component,

\[ R_{E26} = r_{e25} \parallel r_{e27} \parallel r_{e28} = \frac{r_{e25}}{3} = 0.85 \text{k}\Omega \]

\[ R_{C26} = r_{026} \left( 1 + g_{m26} R_{E26} \right) = 4.0 \text{M}\Omega \]

\[ i_{c26} \approx \frac{g_{m26}}{1 + g_{m26} R_{E26}} a_{v21} v_9 \left( \frac{R_{C26}}{R_{C26} + R_{up2} \parallel R_{in3(26)}} \right) \approx \frac{g_{m26}}{1 + g_{m26} R_{E26}} a_{v21} v_9 \]

\[ i_{o2} \approx -\frac{i_{c26}}{3} \]

- Combining these two components, \( i_o = i_{o1} + i_{o2} \)
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- We can find $G_{m2}$ as,

$$G_{m2} \approx a_{v21} \left( \frac{g_{m25}}{1 + g_{m25}R_{E25}} - \frac{g_{m26}}{1 + g_{m26}R_{E26}} \right) = 170 \mu S$$

- The input resistance of the output stage is,

$$R_{i3(25)} = r_{\pi64} + \left( \beta_{npi} + 1 \right)R_{E64}$$

$$R_{E64} = \left[ r_{063} \left( 1 + g_{m63}R_{63} \right) \right] \left( r_{\pi65} + \left( \beta_{pnp} + 1 \right)R_{E65} \right)$$

$$R_{E65} = R_{65} \parallel r_{\pi66} \parallel r_{\pi74} = 200 \Omega$$

$$R_{E64} = 3.5 k\Omega$$

$$R_{i3(25)} = 404 k\Omega$$
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- The output resistance is $R_{o3} = r_{o74} \parallel r_{o75} = 15\,k\Omega$
- The transconductance of the output stage is

$$G_{m3} = a_{v64}a_{v65}g_{m74}$$

$$a_{v64} = \frac{1}{1 + \frac{r_{\alpha64}}{\left(\beta_{npi} + 1\right)R_{E64}}} = 0.36$$

$$a_{v65} = \frac{1}{1 + \frac{r_{\alpha65}}{\left(\beta_{pnp} + 1\right)R_{E65}}} = 0.63$$

$$G_{m3} = \frac{1}{96\Omega}$$
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- Now, let us combine all stages and calculate the gain for a load of $2k\Omega$.

\[ a_{v_1} = G_{m_1} \left( R_{o_1} \left\| \frac{R_{i_2}}{2} \right. \right) = 60 \]

\[ a_{v_2} = 2G_{m_2} \left( R_{o_2} \left\| R_{i_3(25)} \right. \right) = 120 \]

\[ a_{v_3} = G_{m_3} \left( R_{o_3} \left\| R_L \right. \right) = 18 \]

\[ a_v = a_{v_1} a_{v_2} a_{v_3} = 130,000 \]