Low Distortion Design – 3
TIPL 1323
TI Precision Labs – Op Amps

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Prerequisites: Noise 1 – 3
(TIPL1311 – TIPL1313)
Output Stage Topologies

• Most op amps use a Class-AB output stage configuration
  – Classic emitter follower configuration (top), gain = 1.
  – Rail-to-rail output (bottom), gain depends on load resistor.
Output Stage Transfer Function

• The transfer function of the output stage shows 3 distinct regions:
  – Large Signal Regions (Orange)
    • A single device conducts current from the power supply to the load.
  – Clipping Region (Red)
    • Insufficient $V_{CE}$ ($V_{DS}$) drop on output devices to sustain load current
  – Crossover Region (Blue)
    • Both or neither output device conducting current to the load

• All 3 regions will produce some type of distortion

Large Signal Non-Linearity

- Magnified Transfer Function
- Nonlinearity from dissimilar output devices
  - NPN / PNP different transfer functions
Identifying Large Signal Non-Linearity

• Large signal non-linearity dominates at large output voltages
  – Even-order distortion (2\text{nd}, 4\text{th}, 6\text{th}, etc)
  – 2\text{nd} Harmonic is largest

• FFT
  – OPA1652
  – Gain: +1
  – +/-15V Supplies
  – \(V_{\text{OUT}}\): 8.1V_{\text{RMS}}
  – 2\text{nd} Harmonic: -128\text{dB}
Crossover Distortion

- At 0V load current switches from one device to the other
  - Small discontinuity at 0V crossing
  - Produces high-order harmonics
- Worst THD at low output amplitudes and high output currents
  - Load current degrades biasing
  - Low output voltages means crossover region makes up more of the total amplitude
Output Crossover Distortion

- **Test #1**
  - OPA1652
  - Gain: +1
  - +/-15V Supplies
  - $2.5m_{\text{A}_{\text{RMS}}}$ output current
  - $R_{\text{load}}$: 3240 Ohms, $V_{\text{out}}$: 8.1 Vrms
  - THD: -128dB

- **Test #2**
  - OPA1652
  - Gain: +1
  - +/-15V Supplies
  - $2.5m_{\text{A}_{\text{RMS}}}$ output current
  - $R_{\text{load}}$: 32.4 Ohms, $V_{\text{out}}$: 81 mVrms
  - THD: -100dB
**Clipping**

- Collector to emitter drop across output devices:
  - $V_{CE} = V_{OUT} - V_S$
- Insufficient voltage for linear operation.
  - $V_{CE} < V_{CE(SAT)}$
  - Notice $V_{CE(SAT)}$ depends on $I_C$
- Outside of active region:
  - Output stage gain drastically decreases
    - $A_{OL}$ also decreases
  - Output stage distortion increases
    - Typically odd harmonics
- Use the $A_{OL}$ test conditions for linear swing range

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNIT</th>
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</thead>
<tbody>
<tr>
<td>OPEN-LOOP GAIN</td>
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<tr>
<td>$A_{OL}$</td>
<td>Open-loop voltage gain</td>
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<tr>
<td>$V(-) + 0.2 \text{ V} \leq V_0 \leq (V+) - 0.2 \text{ V}, R_L = 10 \text{ kΩ}$</td>
<td>114</td>
<td>130</td>
<td></td>
<td>dB</td>
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<tr>
<td>$V(-) + 0.6 \text{ V} \leq V_0 \leq (V+) - 0.6 \text{ V}, R_L = 2 \text{ kΩ}$</td>
<td>110</td>
<td>114</td>
<td></td>
<td>dB</td>
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</tbody>
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Loading Effects on Transfer Function

- Decreased output stage gain, magnifies dissimilarities in output devices
- Worsens crossover region
- Reduced output swing (increased clipping region)
Loading Effects for Output Distortion

- Output stage distortion appears at high frequency in THD+N curves
  - Mirrors the decline of $A_{\text{OL}}$
- OPA1642 output THD+N
  - Gain: 1
  - $3.5V_{\text{RMS}}$
  - Different load resistors:
    - 10k$\Omega$ (red)
    - 1k$\Omega$ (blue)
    - 500 (green)
- Output loading includes the feedback resistors!
  - Low value feedback resistors increase output distortion
Short Circuit Current?

- Short circuit current only defines the output current with 0V output swing.
- It does not indicate linear output current!
- Example:
  - Device A: 80MHz, 1nV/√Hz, Short circuit current: +55/-62mA
  - Device B: 230MHz, 1nV/√Hz, Short circuit current: 135mA
- Device B shows additional distortion above 1mA_{RMS}
Thermal Distortion

- Possible causes of thermal distortion in IC amplifiers:
  - Dissimilar output device sizes
    - One transistor heats up significantly more during sourcing/sinking
      - Transistor parameters change over temperature
  - Thermal feedback to input stage
    - Input stage is not placed on thermal line of symmetry
      - One input transistor is heated more than the other
THD+N vs Frequency: 50mW, 32 Ohm Load

Increasing distortion at low frequency indicates thermal effects on die
Reducing Output Distortion

• Limit output loading
  – Increase feedback resistor values and load resistance

• Improve crossover distortion performance
  – Increase output voltage swing (not usually an option)
  – Bias output stage into class A with a resistor to the supply (increases power consumption)

• Stay away from clipping regions
  – Maximize supply voltage
  – Confirm linear swing range in datasheet ($A_{OL}$ test conditions)

• Composite Amplifiers
  – Place a buffer inside the feedback loop of another amplifier
    • Increases the amount of loop gain around the output stage
Thanks for your time!
Please try the quiz.