Intrinsic Noise Sources in Chopper Amplifiers

John Caldwell
Applications Engineer, Texas Instruments Precision Analog
Agenda

• Chopper Amplifier Topology
  – Advantages over standard designs

• Chopper Intrinsic Noise Sources
  – Input Current Noise
    • Input Current Noise Calculation
    • Transient Noise
  – Input Voltage Noise
    • Effects of chopping on total integrated noise
    • Chopping in-band vs out-of-band
    • Gain effects

• Application Considerations
Chopper Stabilized Topology

Ripple Magnitude Proportionate to Vos

Slope_pos = (Vos)(gm) /C

Slope_neg = (Vos)(gm) /C

OPA333
125kHz

Average = 0
Engineering Compromises

Advantages

- Low Vos
- Low Vos Drift
- Good CMRR
- Good PSRR
- Good long term drift
- Better Insensitivity to stress, moisture
- No 1/f noise
- Better EMI Immunity

Drawbacks

- Chopper / Auto-Zero feed-through
- Higher Ib
- Transient IB noise
Offset Drift Comparison

- Offset drift comparison between the OPA2188 and the OP2177
  - OP2177 (blue trace) .2uV/°C typical
  - OPA2188 (red trace) .03uV/°C typical
- Chopping allows the OPA2188 to reduce offset drift over temperature by almost 7x
Low Frequency Noise Comparison

- Low-frequency noise comparison between the OPA2188 and the OP2177
  - OP2177 (blue trace) 8nV/rtHz @1kHz → 54nV/rtHz @1Hz
  - OPA2188 (red trace) ~8.8nV/rtHz @1kHz → 11nV/rtHz @1Hz
- Below 100Hz the OPA2188 shows a clear advantage for low-noise precision systems
• Common-mode rejection ratio comparison between the OPA2188 and the OP2177
  - OP2177 (blue trace) 125dB typical
  - OPA2188 (red trace) 134dB typical
- Rectification of EMI in the input differential pair produces additional DC offset
- Screenshots below show the change in offset (blue trace) due to input EMI (yellow trace)
  - OP2177 on left
  - OPA2188 on right
What This Means to Our Customers

- Better Initial Accuracy
  - Improved initial offset
- Better performance in harsh environments
  - Improved rejection of ground/CM noise
  - Improved rejection of EMI
- Fewer recalibrations
  - Greatly reduced drift over time and temperature
Chopper Op Amp Intrinsic Noise Sources

Noise sources in standard op amps
- Input Current Noise (IN1, IN2)
- Input Voltage Noise (VN)

Chopper amplifiers have additional noise sources that should be considered in system design
- Input bias current transients (IB1, IB2)
- Chopper clock feed-through
  - VC1 (input referred when chopping in-bandwidth)

![Op Amp Diagram](image-url)
Current noise on the inputs can be broken into two separate sources
  – Standard input current noise (IN1, IN2)
    • Gaussian distribution
    • Present in all opamps
  – Transient bias current noise (IB1, IB2)
    • Periodic/repetitive
    • Present in devices with input commutation
FET-Input Op Amp Current Noise

- Broadband current noise in FET Input Op Amps can be calculated from the input bias current:

\[ i_n = \sqrt{2 * q * i_B} \]

- \( i_n \): Current Noise Spectral Density
- \( Q \): Charge of an electron (1.6x10^{-19} Coulombs)
- \( i_B \): Input Bias Current

\[ i_n = \sqrt{2 * 1.6 \times 10^{-19} * 5 \times 10^{-12}} = 1.26 fA/\sqrt{Hz} \]
Chopper Input Bias Current is NOT a constant!

Chopper input bias current is actually a periodic waveform consisting of:
- An offset current (actual IB of input circuitry)
- A periodic current waveform from switching

The IB spec in the datasheet is determined by averaging the combination of these two values over a long period of time

Ib Spec = 160pA (typ)
The current noise spectral density spec is only valid, yet pessimistic, below the chopping frequency.

\[ i_n = \sqrt{2q_i B} \]
What causes the Ib spike?

Charge Injection
- When the transistor turns off, the channel charge is dispersed into the source and drain

\[ Q_{ch} = C_{ox} (V_{gs} - V_t) \]
\[ dV_{Qch} = Q_{ch} / 2C_s \]

Clock Feedthrough
- When the transistor turns off, the source voltage is also affected due to the coupling from gate-source capacitance

\[ \Delta V_{Col} = \Delta V_G \times \frac{C_{GS}}{C_{GS} + C_S} \]
Observing Bias Current Spikes

- A wideband transimpedance amplifier (TIA) provides a qualitative examination of the severity of spikes in the IB
  - The chopper is configured as a buffer
  - Non-inverting input is connected directly to the TIA input
- Testing was performed with an OPA657 configured for a gain of 20,000
  - Final gain is 10,000 after impedance matching
  - Output viewed on a 500MHz oscilloscope (50 ohm input)
Observing Bias Current Spikes

\[ V_{OUT} = -\frac{R_F}{2} \left( I_{B(U1)} + I_{B(U2)} + I_{N(U1)} + I_{N(U2)} + I_{Spike} \right) \]

\[ V_{OUT} \approx \frac{-R_F}{2} \left( I_{Spike} \right) = 10,000 \cdot I_{Spike} \]

- Static IB should appear as a DC offset
- Averaging on the oscilloscope can be used to remove Gaussian current noise
- Any repetitive signal in the bias current should dominate the averaged output waveform

<table>
<thead>
<tr>
<th></th>
<th>OPA657</th>
<th>OPA2188</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Current</td>
<td>2 pA</td>
<td>160 pA</td>
</tr>
<tr>
<td>Current Noise</td>
<td>1.3 fA/rtHz</td>
<td>7 fA/rtHz</td>
</tr>
</tbody>
</table>

\[ f_{-3dB} = 60\text{MHz} \]
Investigation Results

- Chopper amplifiers from TI and two competitors were examined
  - OPA2188
  - AD8639
  - MAX44251
- All parts exhibited similar behavior at the inputs
- Very good correlation between IC-level simulation and observed behavior
  - Improvement in future designs
Comparison to Competitor Chopper Amplifiers

Overlaying the input bias spike waveform in the time domain allows for a direct comparison:
- The OPA2188 has the least severe input bias spike of the parts examined
- The MAX44251 displayed the worst performance
Effects on System Performance

• Input current spikes are outside the opamp bandwidth

• Spikes on the Non-Inverting Input:
  – Not amplified
  – May affect high-impedance sensors (sensor becomes transducer)

• Spikes on the Inverting Input:
  – Not amplified
  – The opamp can be removed to simplify analysis of the noise contribution
  – Current noise is coupled to the load through the feedback network
Contribution to Output Noise

Current spikes on the inverting input are coupled to the load by the feedback network.

\[ V_1 = I_{B2} \left( R_G \ || \ R_F + R_{LOAD} \right) \]

\[ V_N = V_1 \left( \frac{R_{LOAD}}{R_F + R_{LOAD}} \right) \]

Output noise is dependant upon:
- Input current spike magnitude
- Feedback network impedance (RF and RG)
- Load Impedance (RLOAD)
Feedback Network Impedance

- Two OPA2188’s were configured for a gain of 11
  - Blue trace → feedback values of 100kOhms and 10kOhms
  - Red trace → feedback values of 1kOhms and 100 Ohms
- Broadband noise reduction is expected from reduced thermal noise of resistances
- Reduction in chopper harmonics due to reduced contribution of transient current noise
Load Impedance Effects

- This plot shows the output noise from the same amplifier circuit (OPA2188) into two different load impedances
  - Red trace is the output noise into a 100 Ohm load
  - Blue trace is the output noise into a very high impedance load (input impedance of OPA211)
- A reduction in the magnitude of the chopper spurs is evident on the low impedance load
Voltage noise on the inputs can be broken into two or three separate sources

- **Standard input voltage noise (VN)**
  - Gaussian distribution
  - Present in all opamps

- **Chopper clock feedthrough**
  - Chopping within amplifier bandwidth → Input referred (VC1)
  - Chopping above amplifier bandwidth → Output referred (VC2)
• The chopper topology modulates the input DC offset to an AC waveform with an average value of zero

• Symmetrical charge and discharge of an output cap produces a triangle wave at the output
  – Consists of a fundamental (chopping frequency) and odd harmonics
Synchronous Notch Filter

- Consider a repetitive waveform in the time domain
  - Zero offset
- The integral over one period of this waveform is zero
  \[\int_{T} \sin(2\pi ft) dt = 0 \implies T = \frac{1}{f}\]
- The integral will also be zero for the harmonics of this waveform
  - Integer multiples of frequency will also integrate to zero over the same period
  \[\int_{T} \sin(n \times 2\pi ft) dt = 0 \implies n = 1, 2, 3, \ldots\]

This concept allows us to build a filter with "notches" at integer multiples of frequency
Synchronous Notch Filter

- The synchronous notch filter integrates the input waveform (on capacitor C) for one clock period
  - Switch Phase 1 closed
  - Switch Phase 2 open
- The integrated value is then passed to the output
  - Switch Phase 1 open
  - Switch Phase 2 closed
- This produces the transfer function shown at right

By synchronizing the switches to the chopping frequency, TI choppers achieve a 500x reduction in noise.
Investigating Chopper Voltage Noise

- Output noise was amplified and viewed in the frequency domain
  - Low Noise Amplifier (LNA) was an OPA211 with a gain of 11
  - Agilent 35670A (.1 to 100kHz)
  - HP3588 (100kHz to 150MHz)
  - Shielded enclosure and cables

- Noise floor is measured first and subtracted from the final results
Synchronous Notch Filter Effectiveness

- OPA2188 Broadband Noise Spectral Density: 8.8 nV/rtHz
- MAX44251 Broadband Noise Spectral Density: 5.9 nV/rtHz

The MAXIM part is lower noise right?....Not Exactly
Gain Effects on Total Noise: Chopping In-Band

- MAX44251: GBW 10MHz, Chopping frequency 65kHz
  - Broadband Noise Spectral Density: 5.9 nV/rtHz
  - Chopper noise scales with gain! → Input referred
Gain Effects on Total Noise: Chopping Out-of-Band

- OPA2188: GBW 3MHz, Chopping Frequency >650kHz
  - Broadband Noise Spectral Density: 8.8 nV/rtHz, synchronous notch filtering
  - Chopper noise scaling with gain is minimal → Output referred
Application Tips
Adding an RC output filter can mitigate noise seen by high impedance loads

- $C_{OUT}$ chosen to have an impedance much less than $R_{LOAD}$ at the chopping frequency
- $R_{OUT}$ chosen to maintain opamp stability with the chosen $C_{OUT}$
Output Filtering

- The contributions of the individual noise sources can be visualized with the circuit at right.

- The corner frequency of the filter as seen by the voltage noise is directly determined by $R_{out}$ and $C_{out}$.

- The corner frequency for the transient current noise is actually much lower.
  - The filter now includes the feedback resistance $R_F$.
  - Filter corner frequency can be chosen to remove current noise without affecting desired signal.
  - $R_G$ also attenuates the noise developed across the load.

System Noise

\[ f_{VC2} = \frac{1}{2\pi R_{OUT} C_{OUT}} \]

Voltage Noise

\[ f_{IB2} = \frac{1}{2\pi (R_{OUT} + R_F) C_{OUT}} \]

Current Noise
Consider the addition of an output RC filter to an OPA2188:

- \( R_F \): 10kOhms, \( R_G \): 100 Ohms
- \( R_{OUT} \): 100 Ohms, \( C_{OUT} \): 10nF

The measurement circuit and calculation of the two corner frequencies created by this filter are shown below:

\[
f_{VC2} = \frac{1}{2\pi \times R_{OUT} \times C_{OUT}} = \frac{1}{2\pi \times 100\Omega \times 10nF} = 159kHz
\]

\[
f_{IB2} = \frac{1}{2\pi \times (R_{OUT} + R_F) \times C_{OUT}} = \frac{1}{2\pi \times (100\Omega + 10k\Omega) \times 10nF} = 1.576kHz
\]
Output Filtering

- Harmonics due to input current spikes are completely eliminated
- Noise at chopping frequency travels through the opamp (not around the feedback network)
Output Filtering

OPA2188 Without Filtering
- Gain: 101, RF:10k, RG:100 Ohm
- Oscilloscope 1MOhm input impedance is the load
- Input current spikes are visible above other noise sources

OPA2188 With Filtering
- Gain: 101 RF: 10k, RG: 100 Ohm
- Oscilloscope 1MOhm input impedance is the load
Comparison to Non-Chopper Amplifiers

The filtered output spectrum of the OPA2188 was compared to a traditional precision bipolar part:
- Removal of the chopping noise makes the high frequency noise spectrum comparable.
Minimizing Chopper Noise Effects

• Input current spikes are not amplified by the part
  – Spikes on the inverting input will be coupled to the load by the feedback network
• Minimize feedback resistance values
  – Reduces the voltage produced by current spikes
  – Standard design practice for low-noise, low-drift circuits
• Load impedance directly contributes to the magnitude of voltage produced by the spike
• An RC filter is an extremely effective way to reduce output noise
  – Most practical with high-impedance loads
  – Corner frequency can be placed outside of the signal bandwidth
  – Noise through the feedback network experiences a much greater attenuation
Thank You!