Application Note

Aliasing and Prevention in Some Capacitively Coupled Current Sense Amplifiers

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ABSTRACT

Many current sense amplifiers (CSA) are based on chopper amplifier architecture. Capacitively coupled current sense amplifiers (CCCSA) are a recent addition to the portfolio. The CCCSA enables low power applications where both quiescent current and input bias current must be minimized. The CCCSA employs a chopping plus auto-zeroing algorithm. Aliasing can occur in such systems where high frequency differential signal is folded into signal band and causes an increase in offset voltage. Aliasing is mitigated with low pass filtering.

Table of Contents

1 Introduction....2
2 Current Sense Amplifier Based on Chopping Techniques....3
3 Aliasing in CCCSA....3
4 Input Filtering....5
5 Summary....6
6 References....6

List of Figures

Figure 1-1. Chopper Amplifier Signal Path....2
Figure 1-2. Chopping Operation on Input Signal....2
Figure 1-3. Chopping Operation on Input Offset....2
Figure 2-1. Input Stage of CCCSA....3
Figure 3-1. INA190 Output with 800kHz Sine Input....4
Figure 3-2. INA190 Output with 790kHz Sine Input....4
Figure 4-1. Low-pass Filter for Anti-aliasing....5
Figure 4-2. Input Filtering on Unit 2....6

Trademarks

1 Introduction

Chopping technique enables improved DC and drift performance. As a result, parameters associated with input offset are enhanced. Low frequency noise is also removed in the modulation and filtering process. Parameters such as V_{os}, CMRR, PSRR are expected to be excellent in CSA based on chopping techniques.

A chopper amplifier is typically made up of two parallel signal paths, a high-gain, low-bandwidth path and a low-gain high-speed path. Figure 1-1 shows a simplified block diagram of a chopping amplifier. Chopping is accomplished in the top low-bandwidth path, while the bottom high-speed path is feed-through, shaping the amplifier gain roll off at high frequencies. At low frequencies, the low-bandwidth path dominates, providing the desired DC precision.

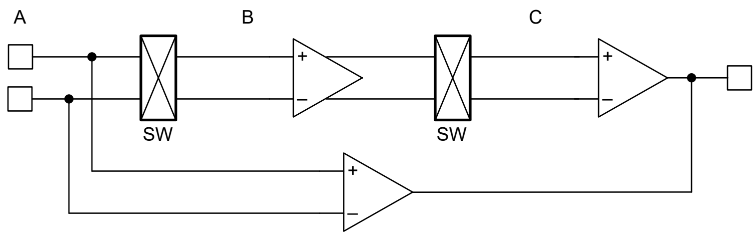


Figure 1-1. Chopper Amplifier Signal Path

For a multi-stage amplifier, input offset is dominated by that of the input stage. Chopping amplifiers achieve offset reduction by employing two pairs of synchronized switches in the signal path.

The working principle on input signal is demonstrated in frequency domain in Figure 1-2. As input signal goes through the chopping operation, a spectrum is plotted for locations A, B and C. The first switch modulates input signal to the chopping frequency and its odd harmonics. The second switch at the output reconstructs the input signal and passes on to the output stage.

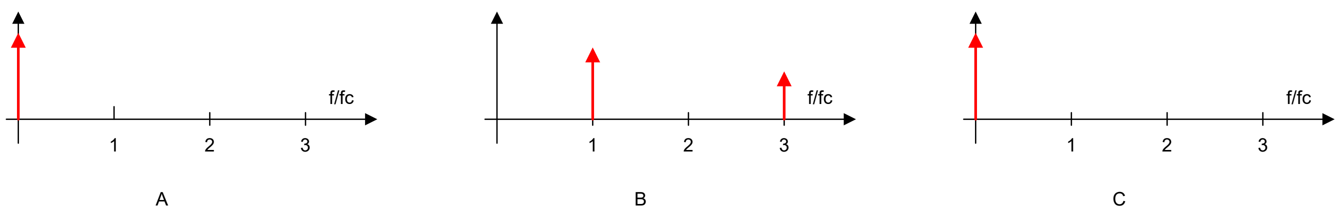


Figure 1-2. Chopping Operation on Input Signal

The offset voltage of the input amplifier, which is modulated to high frequency by the reconstruction switch, is filtered out by a subsequent low-pass filter which is not shown. To contrast with that of input signal, the chopping operation on input offset is illustrated in Figure 1-3. Because offset voltage and 1/f noise are effectively removed, chopping can potentially achieve excellent DC accuracy.

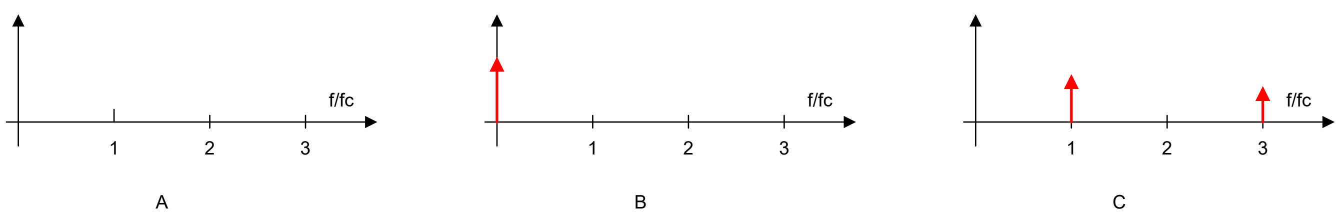


Figure 1-3. Chopping Operation on Input Offset

2 Current Sense Amplifier Based on Chopping Techniques

A chopper-based CSA is constructed by wrapping a precision resistor gain network around a chopper stabilized OpAmp. One unique requirement of CSA is that common mode range must exceed supply voltage. This is done by decoupling the input common mode voltage and supply voltage. At high common mode, the input stage is powered through the common mode voltage source, or the bus voltage source that is being monitored by the CSA. This results in increased input bias current that must be supplied by the bus voltage source, even if the CSA is powered down.

The finite amount of current draw is typically not a problem. However, for low-power applications, or applications where only intermittent monitoring is required, one requirement is to reduce current draw as much as possible.

The main goal of CCCSA is to reduce input bias current while preserving the advantages of chopping amplifier. Figure 2-1 shows the input stage of a CCCSA. Because there is no DC path between Vbus and the input of CCCSA, the DC input bias current is zero. Such devices make a viable option to satisfy the current sensing requirement in low-power applications.

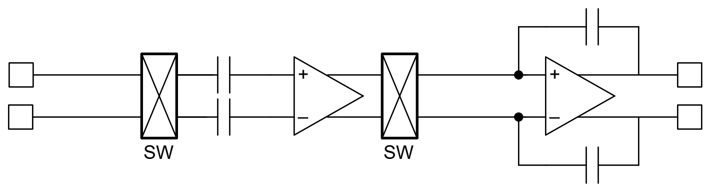


Figure 2-1. Input Stage of CCCSA

For a traditional CSA, the input bias current (sum of both input+ and input-) can be as high as 100uA. Under the same condition, the input bias current of CCCSA is on the order of a few nA. Ultra-low input bias current not only enables low power application, this also enables convenient input low pass filtering without inflicting degradation in system accuracy.

3 Aliasing in CCCSA

In theory, chopping amplifiers operate in a continuous-time manner. Input and output are connected at all times, aliasing does not occur. In reality, design constraints impose physical limitations on these assumptions. Risk of aliasing is minimized through proper design techniques. However, aliasing is still checked for during the silicon verification phase. Time domain and spectrum analysis can be used for this purpose.

In CCCSA, the resistor gain network is replaced by capacitors. To optimize for power and accuracy, the CCCSA takes advantage of a combination of chopping and auto-zeroing. During the zeroing phases, input is effectively disconnected from output. Due to this sample and hold behavior, aliasing can happen when input signal frequency is higher than half the chopping frequency according to Nyquist theorem.

A good application example is switching power supplies, where average output current is to be measured. High frequency switching ripples can fold into signal band when aliasing happens. As a result, the output typically exhibits elevated offset, or low frequency oscillation. Performing FFT on the output waveform also reveals the unwanted tones.

For demonstration purposes, two units of INA190 were tested side by side in this experiment. Both units are driven with the same 20mVpp, 800kHz sinusoidal waveform riding on a DC input to simulate the output of a switching regulator.

Figure 3-1 shows the response of the two units. The top half shows the time domain response (Yellow=Unit 1; Green=Unit 2); the bottom half shows the frequency domain response (Yellow=Unit 1; Purple=Unit 2).

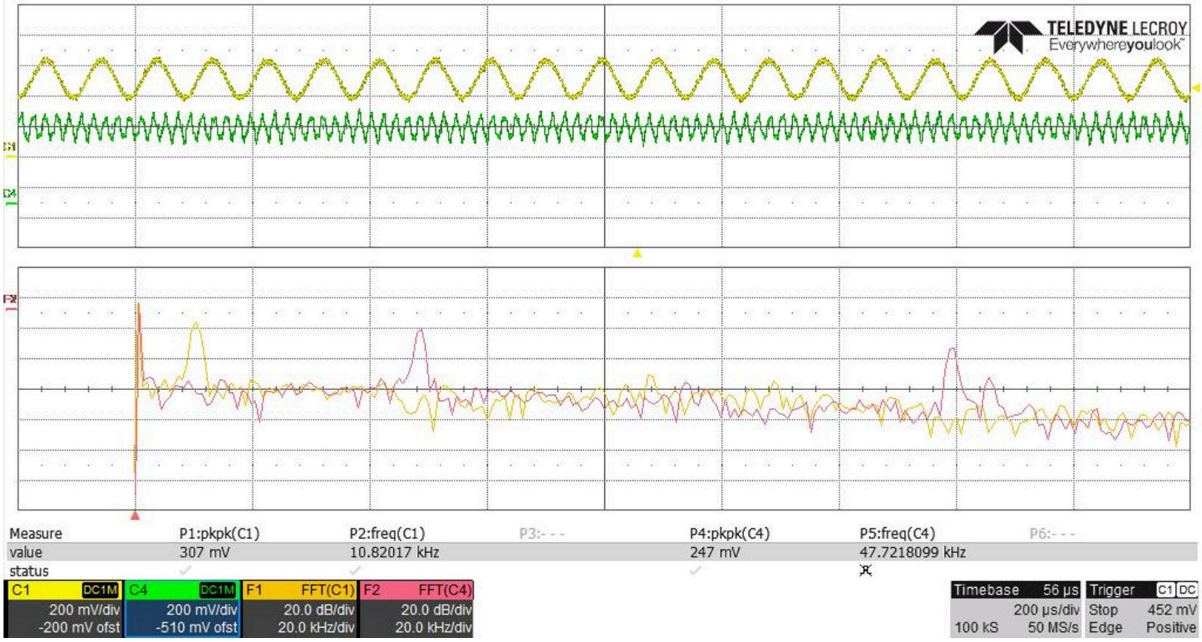


Figure 3-1. INA190 Output with 800kHz Sine Input

The frequency of the harmonics is a function of both the chopping frequency and the input signal frequency. The harmonics are symmetrically located around the chopping frequency and multiples. From this property the chopping frequency can be estimated. Due to device variations, the harmonics frequency varies accordingly. This is why Unit 1 and Unit 2 have very different responses even though the input is identical. Such variation becomes harder to predict when temperature drift is taken into consideration.

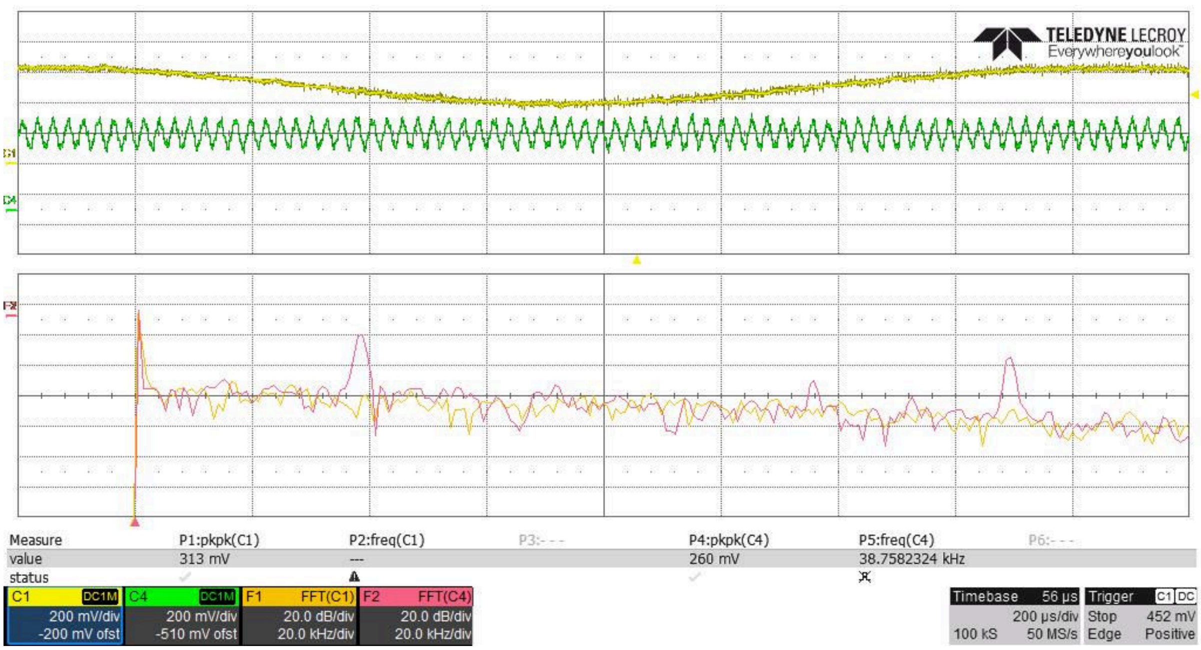


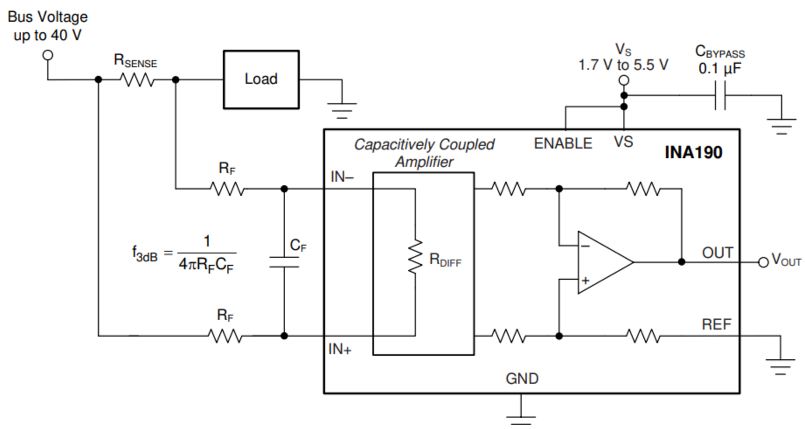
Figure 3-2. INA190 Output with 790kHz Sine Input

Figure 3-2 shows the same setup, where the only difference is to reduce the input signal frequency to 790kHz. The tones shifted by 10kHz. In Unit 1, the shift resulted in an increase in the magnitude of DC output. Such an increase becomes indistinguishable from the true DC output.

4 Input Filtering

An output filter can be effective if there is enough frequency separation between the modulated tones and the desired signal; otherwise, the output filter is not very effective.

Due to factors such as device variation, input signal variation and temperature effect, it is safe to assume that the modulated tones will show up at any frequencies. For this reason, an input filter can be adopted to minimized the risk of aliasing. Figure 4-1 shows a low-pass filter for anti-aliasing, as recommended in the INA190 datasheet. The filter is implemented with two resistors, R_F, and one capacitor, C_F. This filtering scheme can be adopted for INA186 and INA191 when application requires. These devices are based on the same capacitively coupled chopping architecture.



$$f_{3dB} = \frac{1}{4\pi R_F C_F}$$

Figure 4-1. Low-pass Filter for Anti-aliasing

Figure 4-2 shows the effect of such an input filter. In this experiment, the filter is only added to the input of Unit 2, with R_F = 100Ω and C_F = 0.1uF.

The filter corner frequency is approximately 8kHz, providing enough attenuation for the 800kHz input noise. As a general rule, the corner frequency is selected to be the lowest possible allowed by measurement speed requirement. Also, according to Nyquist theorem, the corner frequency needs to be below half the chopping frequency. For the INA190 and family, specified signal bandwidth is well below the chopping frequency.

As Figure 4-2 shows, with anti-aliasing filter in place, Unit 2 output becomes very clean. FFT confirms that the harmonics are effectively removed.

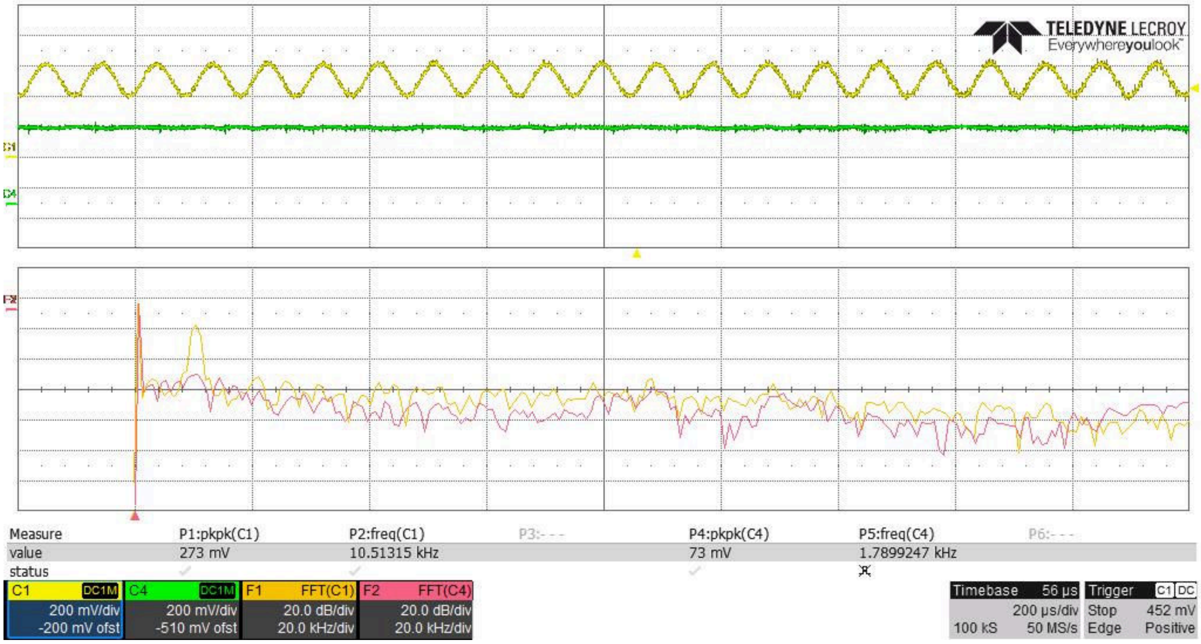


Figure 4-2. Input Filtering on Unit 2

Digital power monitors, if based on the same capacitively coupled chopping techniques, can suffer from similar aliasing effect. Similar to the analog output counterparts, the symptom includes elevated offset, or slow varying offset that is uncharacteristic of random noise. The same input filtering scheme can be employed for anti-aliasing purposes. For example, the INA236 data sheet has a section dedicated to input filtering. It is worth noting that aliasing effect is distinguished from the intrinsic device noise, which is not affected by input filtering.

5 Summary

Capacitively coupled current sense amplifiers combine the advantages of chopping amplifier and switched capacitor circuit to achieve high performance and low power. However, such CCCSA are susceptible to aliasing, especially when sample and hold algorithm is involved in the signal path. When such devices are used in a noisy environment, an input low-pass filter is recommended for anti-aliasing. Resistors used in the low-pass filter can be fairly large, making input filter design flexible. The corner frequency can be placed at or below the device 3dB bandwidth for effective noise attenuation.

6 References

- Texas Instruments *INA190 Bidirectional, Low-Power, Zero-Drift, Wide Dynamic Range, Precision Current-Sense Amplifier With Enable*, datasheet.
- Texas Instruments *INA236 48V, 16-Bit Ultra-Precise, Current, Voltage, and Power Monitor With an I^{2}C Interface*, datasheet.
- R. Burt and J. Zhang, "A Micropower Chopper-Stabilized Operational Amplifier Using a SC Notch Filter With Synchronous Integration Inside the Continuous-Time Signal Path", in IEEE Journal of Solid-state Circuits, Vol. 41, no. 12, December 2006.