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Lowest Noise Zero-Drift Amplifier Has 5.6 nV/√Hz Voltage Noise Density

by Vicky Wong

INTRODUCTION

A sensor typically produces low output voltage and requires a signal conditioning circuit with high gain and accurate dc performance. However, offset voltage, drift, and 1/f noise in amplifiers cause errors, especially for dc or low frequency and low level voltage measurements. Therefore, it is crucial to minimize offset voltage and drift as well as eliminate 1/f noise for optimum signal conditioning. Zero-drift amplifiers, designed to achieve ultralow offset voltage and drift, high open-loop gain, high power supply rejection, high common-mode rejection, and no 1/f noise, provide benefits to designers in precision applications.

AUTO-ZEROING vs. CHOPPING

A zero-drift amplifier, as the name suggests, has a near zero offset voltage drift. The amplifier continuously self-corrects for any dc errors, making it as accurate as possible. A zero-drift amplifier can be designed with two different techniques: auto-zeroing or chopping. Each technique has its benefits and drawbacks and is used in different applications.

Auto-zeroing uses the sample-and-hold technique and has more in-band voltage noise due to noise foldback to the baseband. Alternatively, chopping uses signal modulation and demodulation and has lower baseband noise, but produces noise spectrums at the chopping frequency and its harmonics. As a result, chopper amplifiers are better suited for dc or low frequency applications whereas auto-zero amplifiers are suitable for wider band applications.

ADA4528-1 vs. TRADITIONAL CHOPPER AMPLIFIERS

Traditionally, chopper amplifiers have fairly large baseband noise (refer to Table 1) and low chopping frequencies, limiting their usage to dc and sub-100 Hz applications. For applications that require a chopper amplifier with a larger usable bandwidth, Analog Devices, Inc., released the ADA4528-1, the lowest noise chopper amplifier currently available in the semiconductor industry. The ADA4528-1 employs a novel chopping technique (with an autocorrection feedback loop) and has a chopping frequency that is five to ten times higher than the chopping frequencies of traditional chopper amplifiers.

With a chopping frequency at 200 kHz and an ultralow voltage noise density of 5.6 nV/√Hz, this design breakthrough allows the ADA4528-1 to be used in wider band applications where traditional chopper amplifiers cannot be used in. In addition, the ADA4528-1 also offers 0.3 μV offset voltage, 0.002 μV/°C offset voltage drift, 158 dB common-mode rejection, and 150 dB power supply rejection. These specifications are ideal for applications that require amplication of low level signals in high gain and low noise precision applications. Such applications include precision weigh scales, sensor front ends, load cell and bridge transducers, interface for thermocouple sensors, and medical instrumentation.

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REVISION HISTORY

5/11—Rev. 0 to Rev. A

Added ADA4528-1 vs. Traditional Chopper Amplifiers Section ... 1
Changes to Figure 11 ... 7

4/11—Revision 0: Initial Version

ADA4528-1 CHOPPER ARCHITECTURE

The ADA4528-1 features a novel, patented technique that suppresses offset-related ripple in a chopper amplifier. Unlike other chopper techniques that filter the ripple in the ac domain, this technique nulls the amplifier's initial offset in the dc domain. The ADA4528-1 nulls out the offset with a local feedback loop, referred to as autocorrection feedback (ACFB), thus preventing ripple at the overall output.

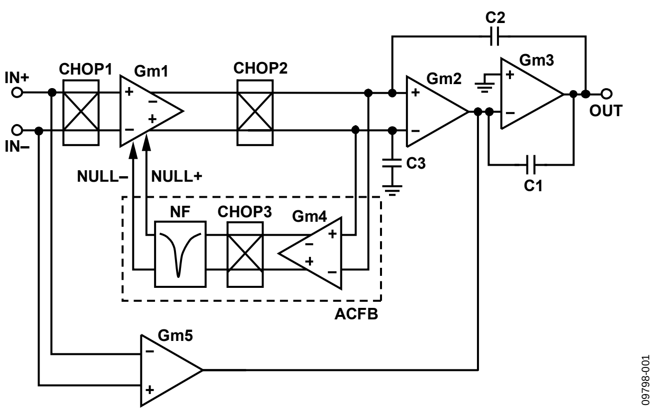

Figure 1. Amplifier Block Diagram

Figure 1 shows the ADA4528-1 amplifier block diagram. It consists of a high dc gain path with autocorrection feedback (ACFB) in parallel with a high frequency feedforward path. The high dc gain path consists of an input chopping switch network (CHOP1), a first transconductance amplifier (Gm1), an output chopping switch network (CHOP2), and second and third transconductance amplifiers (Gm2 and Gm3). The ACFB loop contains a fourth transconductance amplifier (Gm4), a chopping switch network (CHOP3), and a switched capacitor notch filter (NF). Finally, the high frequency feedforward path is made up of a fifth transconductance amplifier (Gm5). The chopping frequency, f_{CHOP}, of all chopping switch networks is designed to operate at 200 kHz.

The input baseband signal is initially modulated by CHOP1. Next, CHOP2 demodulates the input signal and modulates the initial offset and 1/f noise of Gm1 to the chopping frequency. Gm4 in the ACFB loop then senses the modulated ripples at the output of CHOP2. The ripple is demodulated to the dc domain by CHOP3, passed through the notch filter, and fed into the null input terminals of Gm1 (NULL+ and NULL–). Gm1 proceeds to null out the initial offset and 1/f noise, which otherwise appears as modulated ripples at the overall output. This way, the continuous ACFB loop suppresses the modulated ripple.

In addition, CHOP3 modulates the baseband desired signal at the output of CHOP2 to the chopping frequency. The notch filter, synchronized with the clock frequency, filters out signals at the chopping frequency, and thus the modulated components. Therefore, the ACFB loop selectively suppresses unwanted offset voltage and 1/f noise without perturbing the desired input baseband signal.

The high frequency feedforward path functions to amplify any high frequency input signals near or above the chopping frequency. It also bypasses the phase shift introduced by the ACFB loop. As a result, the ADA4528-1 has a standard −20 dB/decade gain roll-off and a unity gain bandwidth of 4 MHz (see Figure 2). This high bandwidth allows the ADA4528-1 to be configured in high gain with sufficient loop gain for minimum gain error.

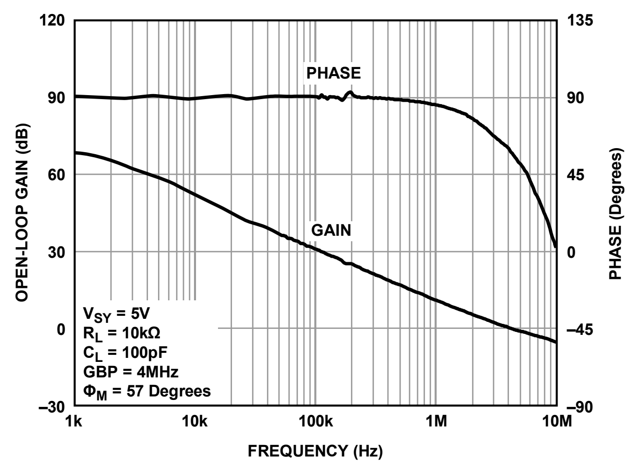

Figure 2. Open-Loop Gain and Phase vs. Frequency

NOISE CHARACTERISTICS

1/F NOISE

1/f noise, also known as pink noise or flicker noise, is inherent in semiconductor devices and increases as frequency decreases. Therefore, it dominates noise at dc or low frequency. The 1/f corner of an amplifier is the frequency at which the flicker noise is equal to the broadband noise. Figure 3 shows an example of an amplifier that does not have the zero-drift technology; the 1/f corner frequency is at 800 Hz. For dc or low frequency applications, 1/f noise is a major noise contributor and can cause a significant output voltage offset when amplified by the circuit noise gain.

Zero-drift amplifiers, however, do not exhibit 1/f noise. They reshape the voltage noise to eliminate 1/f noise. Because 1/f noise appears as a slow varying offset, it can be effectively eliminated by the chopping technique. The correction becomes more effective as the noise frequency approaches dc, eliminating the tendency of the noise to increase exponentially as frequency decreases. Figure 4 shows the voltage noise density of the ADA4528-1 with no 1/f voltage noise. The chopping technique results in the ADA4528-1 having only 97 nV p-p of voltage noise from 0.1 Hz to 10 Hz at a supply voltage of 2.5 V, much lower noise at low frequency than standard low noise amplifiers that are susceptible to 1/f noise.

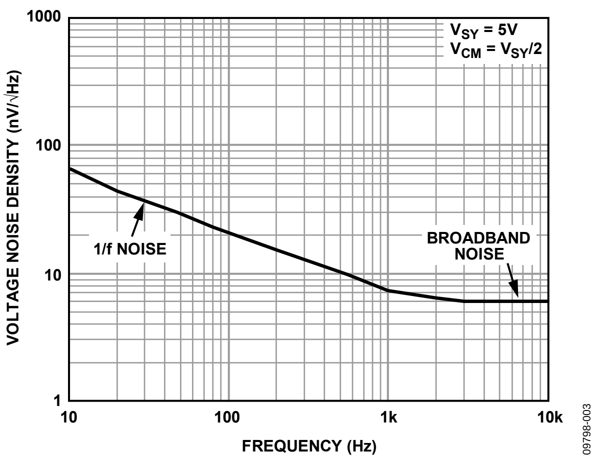

Figure 3. Non zero-Drift Amplifier: Voltage Noise Density vs. Frequency

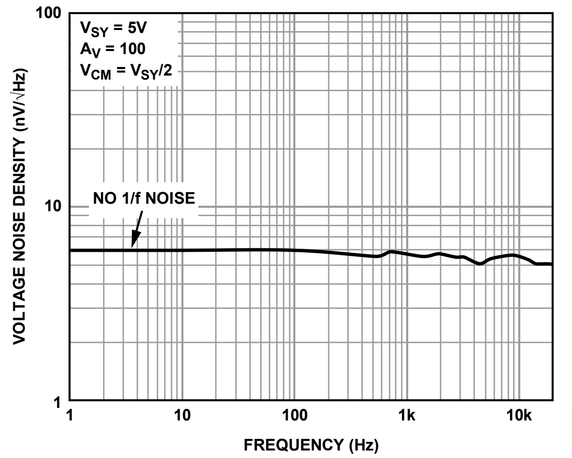

Figure 4. ADA4528-1 Zero-Drift Amplifier: Voltage Noise Density vs. Frequency

BROADBAND NOISE AND EXTERNAL SOURCE RESISTANCE CONSIDERATIONS

The ADA4528-1 is the lowest noise zero-drift amplifier currently available in the industry with 5.6 nV/√Hz of voltage noise density at 1 kHz (at V_{SY} = 2.5 V, A_V = 100). It is, therefore, important to consider the external input source resistance to maintain total low noise performance of the system.

The total input referred noise (e_n total) that must be considered in any amplifier design is primarily a function of three types of noise: input voltage noise, input current noise, and thermal (Johnson) noise from the external resistors. The input voltage noise and input current noise are usually stated in the electrical specifications section of a data sheet. The thermal noise of an external source resistor can be calculated from the following equation:

$$V_{RS} = \sqrt{4\ kTR_S}$$

where:
k is the Boltzmann constant (1.38×10^{-23} J/K).
T is the temperature in Kelvin (K).
R_S is the total input source resistance (Ω).

The three uncorrelated noise sources can be summed up in a root sum squared (rss) manner in the following equation:

$$e_n\ total = \sqrt{[e_n^2 + 4\ kTR_S + (i_n \times R_S)^2]}$$

where:
e_n is the input voltage noise of the amplifier (V/√Hz).
i_n is the input current noise of the amplifier (A/√Hz).

The total equivalent rms noise over a specific bandwidth is expressed as

$$e_{n,RMS} = e_n\ total \sqrt{BW}$$

where BW is the bandwidth in hertz.

This analysis is valid for a flatband noise calculation. If the bandwidth of concern includes the chopping frequency, more complicated calculations must be made to include the effect of the noise spectrum at the chopping frequency (see Figure 8).

Voltage noise density is sometimes dependent on the amplifier gain configuration. Figure 5 shows the voltage noise density vs. closed-loop gain of a zero-drift amplifier of a leading competitor. The voltage noise density of the amplifier increases from 11 nV/√Hz to 21 nV/√Hz as closed-loop gain decreases from 1000 to 1. Figure 6 shows the voltage noise density vs. frequency of the ADA4528-1 for three different gain configurations, A_V = 1, 10, and 100. The ADA4528-1 offers a constant voltage noise density of 6 nV/√Hz to 7 nV/√Hz regardless of gain configurations.

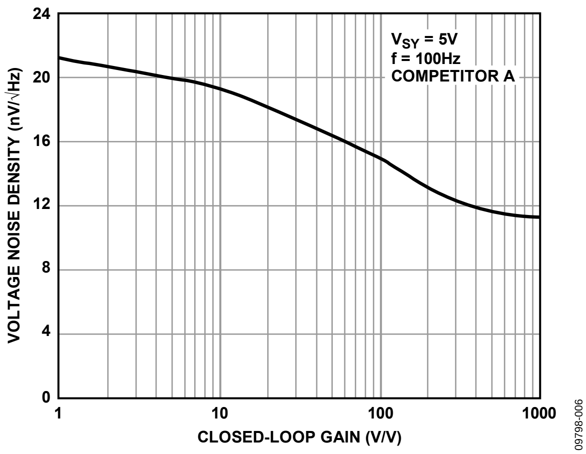

Figure 5. Competitor A: Voltage Noise Density vs. Closed-Loop Gain

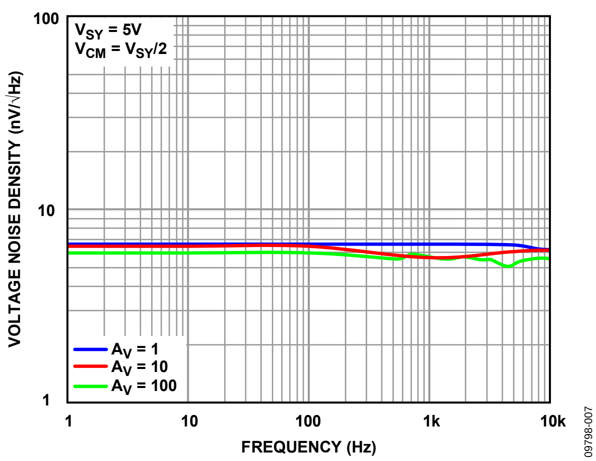

Figure 6. ADA4528-1: Voltage Noise Density vs. Frequency

CALCULATION OF NOISE CONTRIBUTION REFERRED TO THE OUTPUT

Figure 7 shows the ADA4528-1 in a noninverting configuration. A calculation of noise contribution from the external resistors, amplifier voltage, and current noise referred to the output (RTO) is as follows:

Noise gain $= 1 + R_F/R_S$

$V_{RS} = \sqrt{4\,kTR_S}$

$V_{RF} = \sqrt{4\,kTR_F}$

Error due to R_S thermal noise $= V_{RS} \times R_F/R_S$

Error due to R_F thermal noise $= V_{RF}$

Error due to amplifier voltage noise $= e_n \times (1 + R_F/R_S)$

Error due to amplifier current noise $= i_n \times R_F$

Refer to Table 1 for calculation results.

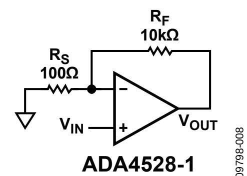

Figure 7. Noninverting Gain Configuration

Table 1. Calculated Output Noise (V_{SY} = 5 V)

Noise Source	Value (at f = 1 kHz)	Thermal Noise (nV/√Hz)	Total Noise RTO (nV/√Hz)	Output Noise Contribution (%)
R_S	100 Ω	1.283	128.3	4.43
R_F	10 kΩ	12.83	12.83	0.04
Voltage Noise	5.9 nV/√Hz	N/A[1]	595.9	95.52
Current Noise	0.5 pA/√Hz	N/A[1]	5	0.01

[1] N/A means not applicable.

VOLTAGE RIPPLE

Although chopper amplifiers null out initial offset voltage, voltage ripples still exist. Two sources contribute toward these voltage ripples.

First, the voltage ripple is part of the residual ripple associated with the initial offset Gm1 (see Figure 1). This ripple creates higher noise spectrums at the chopping frequency (200 kHz) and its harmonics. Figure 8 shows the voltage noise density of the ADA4528-1 vs. frequency in three different gain configurations. The amplifier in the unity gain configuration has a noise spectrum of 50 nV/√Hz at 200 kHz. This noise spectrum is significant when the op amp has a closed-loop bandwidth that is greater than the chopping frequency. However, with a higher gain, the noise spectrum becomes less significant due to the natural gain roll-off characteristic of the amplifier. Therefore, the ADA4528-1 is excellent for use in dc high gain configuration with its ultralow noise, offset voltage, and drift capability.

To suppress noise at the output, place a feedback capacitor around the amplifier. Figure 9 and Figure 10 show the configuration and the corresponding voltage noise density vs. frequency graph. The feedback capacitor reduces the amplifier bandwidth in an effort to reduce noise.

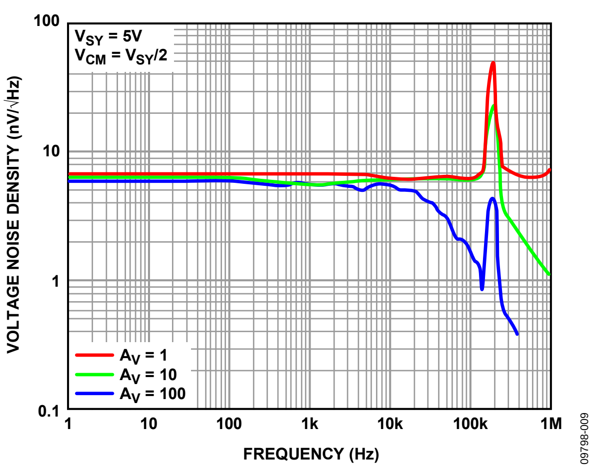

Figure 8. Voltage Noise Density vs. Frequency at Different Closed-Loop Gains

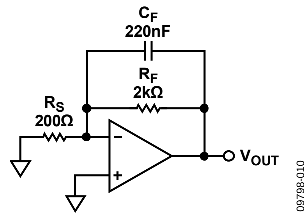

Figure 9. Reducing Noise Using a Feedback Capacitor

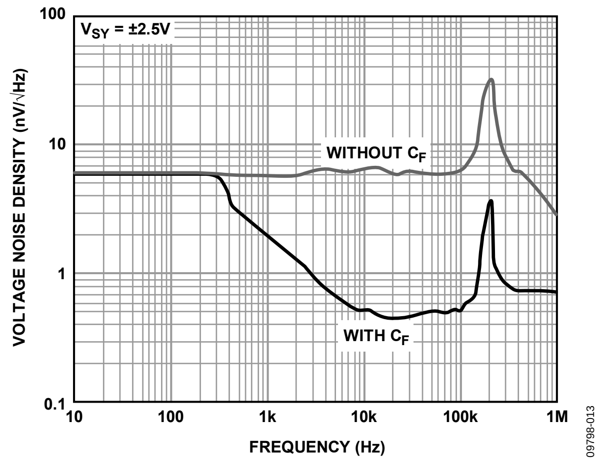

Figure 10. Voltage Noise Density with Feedback Capacitor

The second source of voltage ripple is the result of intermodulation between the chopping frequency (f_{CHOP}) and the input signal frequency (f_{IN}). Intermodulation distortion (IMD) is a function of the input signal frequency, and larger errors are introduced as the input signal frequency approaches the chopping frequency. This intermodulation creates a noise spectrum at the second-order IMD products at $f_{CHOP} \pm f_{IN}$, third-order IMD products at $2f_{IN} \pm f_{CHOP}$ and $2f_{CHOP} \pm f_{IN}$, and so on. The ADA4528-1 produces very low intermodulation distortion in comparison to other zero-drift amplifiers. An input signal of 500 mV p-p voltage at 180 kHz produces 14.6 μV rms of distortion at 20 kHz.

In addition, note that all zero-drift amplifiers are susceptible to residual ripple of the initial offset and intermodulation distortion.

ADA4528-1 AS AN INSTRUMENTATION AMPLIFIER

The extremely low offset voltage and drift, high open-loop gain, high common-mode rejection, and high power supply rejection of the ADA4528-1 make it an excellent op amp choice as a discrete, single-supply instrumentation amplifier.

Figure 11 shows the classic 3-op amp instrumentation amplifier using the ADA4528-1. The key to high CMRR for the instrumentation amplifier are resistors that are well matched for both the resistive ratio and relative drift. For true difference amplification, matching of the resistor ratio is very important, where R5/R2 = R6/R4. The resistors are important in determining the performance over manufacturing tolerances, time, and temperature. Assuming a perfect unity gain difference amplifier with infinite common-mode rejection, a 1% tolerance resistor matching results in only 34 dB of common-mode rejection. Therefore, at least 0.01% or better resistors are recommended.

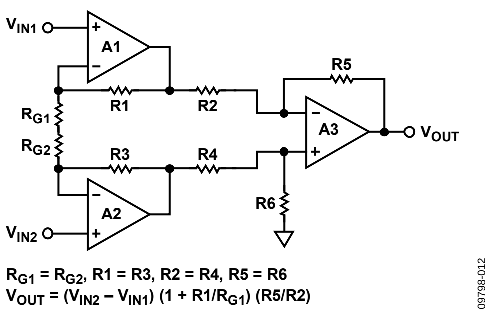

Figure 11. Discrete 3-Op Amp Instrumentation Amplifier

To build a discrete instrumentation amplifier with external resistors without compromising on noise, pay close attention to the resistor values chosen. R_{G1} and R_{G2} each has thermal noise that is amplified by the total noise gain of the instrumentation amplifier and, therefore, should be chosen sufficiently low to reduce thermal noise contribution at the output and yet provide an accurate measurement. Table 2 shows the external resistors noise contribution referred to the output (RTO).

Table 2. Thermal Noise Contribution Example

Resistor	Value (Ω)	Resistor Thermal Noise (nV/√Hz)	Thermal Noise RTO (nV/√Hz)
R_{G1}	400	2.57	128.30
R_{G2}	400	2.57	128.30
R1	10 k	12.83	25.66
R2	10 k	12.83	25.66
R3	10 k	12.83	25.66
R4	10 k	12.83	25.66
R5	20 k	18.14	18.14
R6	20 k	18.14	18.14

Note that A1 and A2 have a high gain of 1 + R1/RG1. In this case, the input offset voltage and the input voltage noise of the amplifiers are important. Similar to R_{G1} and R_{G2}, the input offset voltage and the input voltage noise of the amplifiers are amplified by the overall noise gain. Therefore, use a high precision, low offset voltage and low noise amplifier for A1 and A2, such as the ADA4528-1. On the other hand, A3 operates at a much lower gain and has a different set of op amp requirements. Its input noise, referred to the overall instrumentation amplifier input, is divided by the first stage gain and is not as important.

For dc and low frequency application that requires minimal voltage drift, use zero-drift amplifiers, such as the AD8538 or AD8628 for A3. If voltage drift is not a concern, use the AD8603.

CONCLUSION

In summary, the main features of the ADA4528-1 are

- Ultralow offset voltage and drift
- No 1/f voltage noise
- Ultralow voltage noise density
- High common-mode rejection
- High power supply rejection
- Rail-to-rail input and output

The design architecture specifically targets high gain precision signal conditioning applications that require accurate and stable performance in the dc or low frequency bandwidth.

For a selection of other zero-drift amplifiers, see Table 3.

For a low noise op amp selection table, refer to the AN-940 Application Note, *Low Noise Amplifier Selection Guide for Optimal Noise Performance.*

For more information on noise, watch the three-part webinar series, *Noise Optimization in Sensor Signal Conditioning Circuits*.

- Part 1: www.analog.com/webcast_noiseopt_part1
- Part 2: www.analog.com/webcast_noiseopt_part2
- Part 3: www.analog.com/webcast_noiseopt_part3

Table 3. Single Zero-Drift Amplifiers

Part Number	V_{SY} (V)	V_{OS} Max (µV)	TCV_{OS} Max (µV/C)	GBP (MHz)	I_{SY}/Amp Max (mA)	e_N at 1 kHz (nV/√Hz)	CMRR Min (db)	PSRR Min (db)	I_B Max (pA)	R-R In	R-R Out
ADA4528-1	2.2 to 5.5	2.5	0.015	4	1.7	5.6	135	130	400	Yes	Yes
AD8628	2.7 to 5	5	0.02	2	1	22	110	115	100	Yes	Yes
AD8638	5 to 16	9	0.06	1.35	1.3	60	118	127	40	No	Yes
AD8538	2.7 to 5.5	13	0.1	0.43	0.18	50	110	105	25	Yes	Yes
ADA4051-1	1.8 to 5.5	15	0.1	0.115	0.018	95	105	110	50	Yes	Yes