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APPLICATION NOTE

Design Considerations and Solutions for Headphone Drivers in Mobile Phones

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INTRODUCTION

High fidelity describes the quality of audio equipment. High fidelity audio equipment has ideal total harmonic distortion plus noise (THD + N) performance and accurate frequency response, resulting in excellent subjective test results.

Portable high fidelity audio equipment brings customers a higher quality music listening experience. Compared to mobile phones, however, portable high fidelity audio equipment is inconveniently large. Though given increased market demand and technical advances, it is now possible to integrate the high fidelity function into thinner mobile phones.

Typically, audio digital-to-analog converters (DACs) cannot drive low impedance headphones well. However, to reach quality performance, operational amplifiers are used with audio DACs for signal conditioning, including current to voltage (I to V) conversion, filter, attenuation, and differential to single-ended conversion. The operational amplifiers must have low noise, low distortion, and strong drive capability. The operational amplifier must also perform well in subjective testing with customers. Many Analog Devices, Inc., operational amplifiers are reputable with music fans, like the AD797, OP275, AD8620, and ADA4627-1. In portable mobile phone applications, the quiescent current and package of a device is important. The ADA4841-2, ADA4896-2, ADA4075-2, ADA4807-2, and AD8397 have ideal noise and distortion performances. This application note focuses on the circuit discussion and operational amplifier recommend-dations for this high fidelity headphone driver application.

SIGNAL CHAIN

In this type of application, use high performance and low power audio DACs to deliver a dynamic range (DNR) of up to 127 dB and THD + N of −120 dB. Some high performance audio DACs can be configured as a voltage output or current output. Configure current output for better DNR and THD + N.

For a voltage output configuration, the conditioning circuit is a different amplifier circuit, which converts the differential signal from the R channel or L channel to a single-ended signal (see Figure 1).

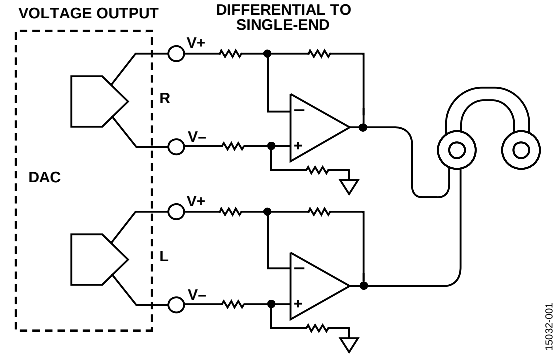

Figure 1. Voltage Output Configuration

For a current output configuration, implement an I to V circuit to convert the differential current signal from the R channel and the L channel to the differential voltage signal, followed by a difference amplifier circuit (see Figure 2).

In mobile phone applications, the power consumption of devices is key. In this application note, a ±5 V power is chosen as the example for analysis convenience.

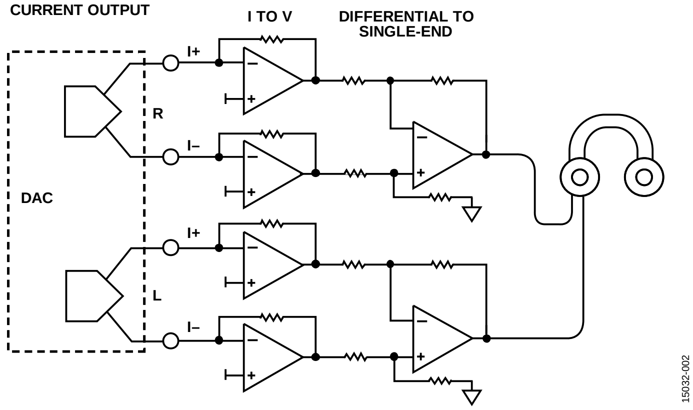

Figure 2. Current Output Configuration

TABLE OF CONTENTS

REVISION HISTORY

10/2016—Revision 0: Initial Version

I TO V STAGE

An ideal I to V converter for a current output DAC is a resistor to ground. However, most DACs do not operate linearly with voltage at the output. It is standard practice to operate an operational amplifier as an I to V converter, creating a virtual ground at the inverting input. Normally, the operational amplifier output stage absorbs clock energy and current steps. However, Figure 3 shows the C_F capacitor shunts high frequency energy to ground while correctly reproducing the desired output with extremely low THD and intermodulation distortion (IMD).

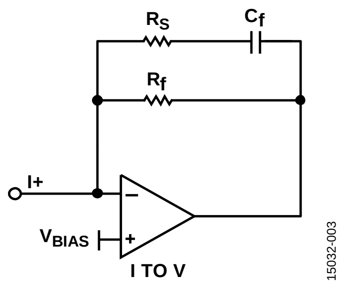

Figure 3. I to V Stage

There are four components in the circuit:

- R_F is the feedback resistor. For lowest noise, maximize gain in the first stage (I to V). However, distortion is related to the open-loop gain (A_{OL}) of the operational amplifier. The higher A_{OL}, the better the distortion performance. Normally, A_{OL} is specified within certain output voltages (see Figure 3). The ADA4896-2 A_{OL} must be 100 dB minimum when the output is −4 V to 4 V at ±5 V power supply, or when distortion increases beyond −4 V to 4 V. Assuming the maximum output current of a DAC is 1 mA, then,

$$R_F = \frac{V_{OUT}}{I_{OUT}} = \frac{4\text{ V}}{1\text{ mA}} = 4\text{ k}\Omega$$

- C_F is the feedback capacitor in parallel with R_F. C_F and R_F form a pole in the transfer function, therefore the cutoff frequency (f_C) of the low-pass filter is

$$f_C = \frac{1}{2\pi R_F C_F}$$

Assuming f_C is 100 kHz, then,

$$C_F = \frac{1}{2\pi R_F f_C} = \frac{1}{2\pi \times 4\text{ k}\Omega \times 100\text{ k}\Omega} \approx 390\text{ pF}$$

- R_S is the resistor in series with C_F. Typically, R_S = 100 Ω for better stability and THD + N performance.
- V_{BIAS} is the voltage bias. Typically, audio DACs generate a dc offset current. For maximizing the effective output signal, add a V_{BIAS} at the noninverting input terminal to cancel the dc voltage by the DAC dc offset current.

OPERATIONAL AMPLIFIER RECOMMENDATIONS FOR I TO V STAGE IN MOBILE PHONES

The key specifications of operational amplifiers as the I to V stage in headphone drivers include power supply, I_Q, voltage and current noise, THD + N, package, common-mode rejection ratio (CMRR), power supply rejection ratio (PSRR), A_{OL}, and slew rate. The ADA4841-2, ADA4896-2, ADA4075-2, and ADA4807-2 are recommended for I to V conversion. Key points about these devices include the following:

- All devices are low noise, low power, and have a small package.
- ADA4807-2 uses the lowest I_Q to achieve low noise and rail-to-rail input/output (RRIO) and it integrates the disable function, which can further decrease the power consumption.
- The ADA4075-2 specified power supply is 9 V minimum, is not a rail-to-rail output (RRO), and has the smallest package.
- THD + N is the key specification. See Figure 4 and Figure 5 for the test circuit and test result of THD + N, respectively.

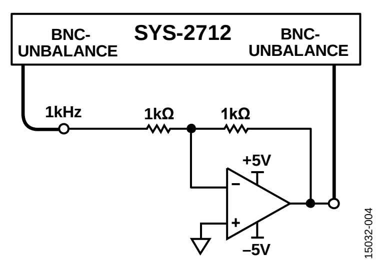

Figure 4. THD + N Test Without Load

THD + N VS. V_{OUT} MEASUREMENT

To determine the maximum output without THD + N degrading, measure THD + N vs. V_{OUT}.

Typically, an audio DAC current output acts as a resistor in series with a voltage source. That is, the I to V circuit can be considered an inverting amplifier circuit. For simplicity, gain = −1 to determine the THD + N performance of operational amplifiers (see Figure 5). The following details the procedure to measure THD + N vs. V_{OUT} using the SYS-2712 from Audio Precision:

- The power supply is ±5 V.
- The SYS-2712 analog analyzer generates a 1 kHz sine wave as the input of the amplifier circuit. The output of the amplifier circuit feeds into the SYS-2712 to obtain THD + N data.
- The bandwidth of the SYS-2712 analyzer is configured as 22 kHz.
- To find THD + N at the output range in the SYS-2712 evaluating software, the input of the analog analyzer is configured as autorange, that is, the input stage gain of the analyzer increases automatically by the different input signals, including 40 mV, 160 mV, 300 mV, 600 mV, 1.2 V, 2.5 V, and 5 V. Typically, the larger the gain, the worse the noise level of the analyzer and THD + N.

THD + N VS. V_{OUT} RESULT

Figure 5 shows THD + N vs. V_{OUT} results for the recommended operational amplifiers. When V_{OUT} is less than 1.2 V rms, THD + N performance of the four operational amplifiers is similar.

When V_{OUT} is larger than 1.2 V rms, the analog analyzer of the SYS-2712 is switched to 2.5 V scale, increasing the gain of internal programmable gain amplifier (PGA). The noise worsens and THD + N degrades slightly. The SYS-2712 causes this degradation. This is not the true performance of the operational amplifier because the SYS-2712 has worse noise with a larger PGA gain.

As V_{OUT} continues to increase, THD + N degrades dramatically at the maximum output voltage of the amplifier. For the ADA4841-2, ADA4896-2, and ADA4807-2, the voltage is about 3.5 V rms (4.9 V peak). This matches the RRO feature of these devices. For the ADA4075-2, the voltage is about 2.13 V rms (3.0 V peak). This matches the 2 V output voltage to the rail in the ADA4075-2 data sheet.

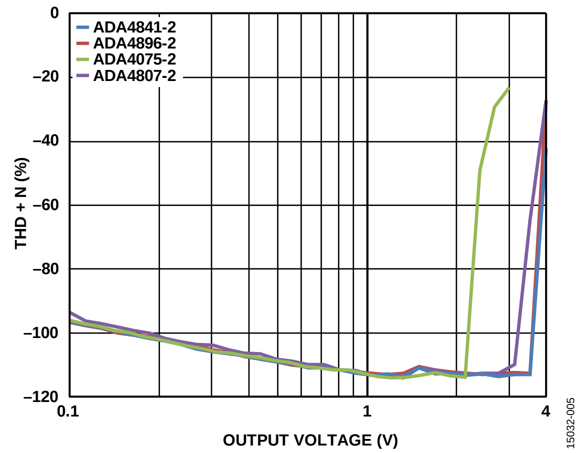

Figure 5. THD + N Result of Recommended Operational Amplifiers

HEADPHONE BASICS

The characteristics of load (headphones) determines the output stage. The headphones have two key specifications: impedance and sensitivity.

Impedance is typically measured at 1 kHz. Low impedance headphones are in the range of 8 Ω to 32 Ω. High impedance headphones are in the range of about 100 Ω to 600 Ω. As the impedance increases, more voltage (at a given current) is required to drive it. As a result, the loudness of the headphones for a given voltage decreases. In recent years, impedance of newer headphones has generally decreased to accommodate lower voltages available on battery-powered portable electronics, like mobile phones. Lower impedance means heavier load to the operational amplifier, which requires operational amplifiers to have larger current drive capabilities without distortion.

Sensitivity measures how loud the headphones are for a given electrical drive level. It can be measured in decibels of sound pressure level (SPL) per milliwatt (dB/mW) or decibels of SPL per volt (dB/V).

By analyzing the wave file of a live recording, the maximum SPL can reach 120 dB. The average SPL is less than 100 dB. Find the required peak power using the following formula:

$$P = 10\left(\frac{Required\ SPL - Sensitivity}{10}\right)$$

Table 1 details the key specifications of some headphones. The impedance ranges from 8 Ω to 600 Ω. The required peak power, peak voltage, and peak current are listed.

The required average power is less than 2 mW. To reproduce the effect of live recording, the headphone driver must output more power. See Table 1.

For low impedance headphones, the required peak current can reach 80 mA maximum, and THD + N of the current cannot degrade.

For high impedance headphones, the output voltage must be high. For example, using the DT880 from Beyer Dynamic (600 Ω) requires an operational amplifier output of 12 V, which is impossible in a ±5 V system. If the product targets driving high impedance headphones, increase the power supply of the amplifier circuit.

Table 1. Sensitivity, Impedance, Peak Voltage, and Peak Current of Headphones

Manufacturer	Model	Sensitivity (dB/mW)	Impedance (Ω)	Frequency (Hz)	Average Power (mW)	Peak Power (mW)	Peak Voltage (V)	Peak Current (mA)
SONY	XBA-4	108	8	3 to 28000	0.158	15.849	0.356	44.510
Audio-Technica	ATH-CHX7	100	16	15 to 22000	1.000	100.000	1.265	79.057
Shure	SE215	107	20	22 to 17500	0.200	19.953	0.632	31.585
Apple	Earpod	109	23	5 to 21000	0.126	12.589	0.538	23.396
Grado	Alice M1	100	32	20 to 22000	1.000	100.000	1.789	55.902
Creative	AURVANA Air	102	32	20 to 20000	0.631	63.096	1.421	44.404
KOSS	PP	101	60	10 to 25000	0.794	79.433	2.183	36.385
Sennheiser	HD650	98	300	10 to 39500	1.585	158.489	6.895	22.985
Beyer Dynamic	DT880	96	600	5 to 35000	2.512	251.189	12.277	20.461

OUTPUT STAGE (FIRST-ORDER LOW-PASS FILTER)

The output stage converts the differential voltage signal to the single-ended voltage signal. Figure 6 depicts a common difference amplifier circuit, also known as a subtractor circuit.

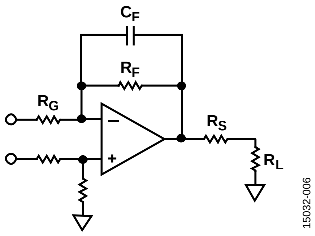

Figure 6. Differential Single-Ended Circuit

R_G and R_F determine the gain of the circuit, which is normally gain < 1. The resistance of resistors must be small, typically 1 kΩ, to avoid inducing more noise. R_F and C_F forms a pole in the transfer function. Therefore, f_C of the low-pass filter is

$$f_C = \frac{1}{2\pi R_F C_F}$$

R_S determines the output impedance or the damping factor of the headphone driver. The high damping factor (R_L/R_S) improves the control the source (headphone driver) has over the load (headphone). The impedance of the headphone does not have pure resistance and varies by frequency. A higher R_S can induce more distortion (especially low frequency distortion) because of the frequency varied impedance. From a performance perspective, make R_S low. Generally, the damping factor remains above one.

From a safety perspective, higher R_S can attenuate power to protect the headphone from damaging, while also protecting the amplifier in case the output shorts to ground. This can happen when hot plugging the headphones. Figure 7 shows the ADA4807-2 (LFCSP) maximum power dissipation vs. ambient temperature for a 4-layer evaluation board.

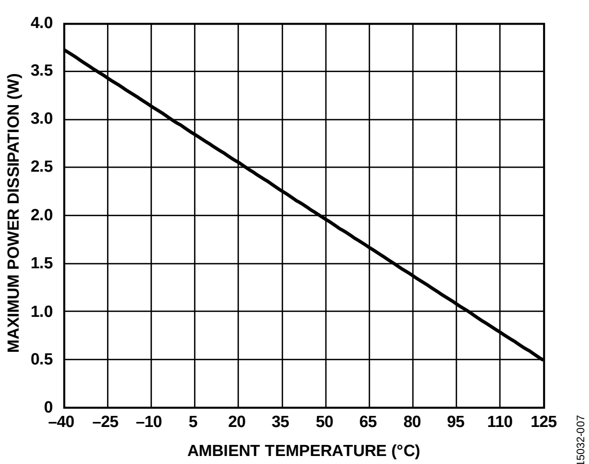

Figure 7. ADA4807-2 Maximum Power Dissipation vs. Ambient Temperature for a 4-Layer Evaluation Board

Power dissipation (P_D) can be 1.274 W at 85°C ambient temperature. Assuming ±5 V is the power supply, the maximum output voltage is 2 V rms. R_S = 10 Ω, and R_S is shorted to ground. P_D per channel of the ADA4807-2 is

$$P_D = (V_S \times I_S) + \left(\frac{V_S}{2} \times \frac{V_{OUT}}{R_L}\right) - \frac{V_{OUT^2}}{R_L}$$

P_D = 610 mW

Considering the ADA4807-2 is a dual-channel device, the total P_D is 1.22 W. The output current in this example is 200 mA. The ADA4807-2 short-circuit current is 80 mA, so R_S can be smaller to increase the damping factor. For operational amplifiers with a short-circuit current larger than 200 mA, RS must be 10 Ω minimum to avoid operational amplifier damage in output short to ground status**.**

OUTPUT STAGE (SECOND-ORDER LOW-PASS FILTER)

Compared to the first-order low-pass filter, the second-order low-pass filter has a steeper roll-off response, removing more noise out of the specified band.

The two-pole low-pass filter with differential input is easily designed using the design equations for the single-ended input multiple-feedback low-pass filter. Shown in Figure 8, duplicating the component results in an equivalent frequency response. Normally, the filter gives a Bessel response, which has a linear phase.

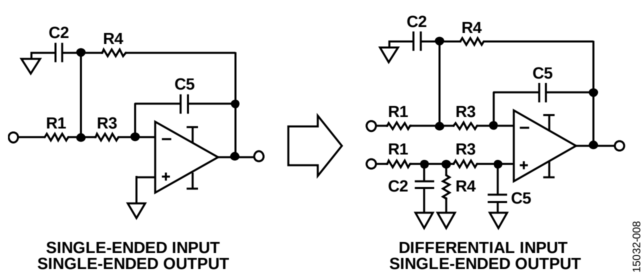

Figure 8. Second-Order Multiple Feedback (MFB) Filter

OPERATIONAL AMPLIFIER RECOMMENDATIONS FOR OUTPUT STAGE

The key specifications for the output stage operational amplifier is similar to the I to V stage. The output stage operational amplifier must typically have <−100 dB THD + N at 32 Ω load. The ADA4841-2, ADA4807-2, and AD8397 operational amplifiers are recommended for the output stage of headphone drivers in mobile phones. There are four points to consider:

- All of the operational amplifiers are low noise, low power, and small package devices.
- ADA4807-2 achieves low noise and RRIO by lowest I_Q. It also integrates a disable function, which can further decrease power consumption.

- AD8397 typically has <−100 dB THD + N at 32 Ω load. It also tests subjectively well. The disadvantage is the AD8397 I_Q is higher, at about 12 mA.
- <−100 dB THD + N at 32 Ω load is a key specification. See Figure 9 and Figure 10 for the test circuit and test result, respectively.

See the ADA4841-2, ADA4807-2, and AD8397 data sheets for relevant specifications.

THD + N VS. V_{OUT}/I_{OUT} MEASUREMENT

Figure 9 shows the circuit used to find THD + N at a heavy load. The following details the THD + N vs. V_{OUT}/I_{OUT} measurement:

- The power supply is ±3.3 V. The gain of the subtractor is about 0.243.
- The SYS-2712 generates a 1 kHz sine wave as the input of the amplifier circuit. Feed the output of the amplifier circuit into the SYS-2712 analog analyzer to determine THD + N.
- Configure the bandwidth of the SYS-2712 analyzer to 22 kHz.
- To measure THD+N vs. V_{OUT}/I_{OUT}, SYS-2712 is configured to output a 100 mV rms to 4 V rms signal.

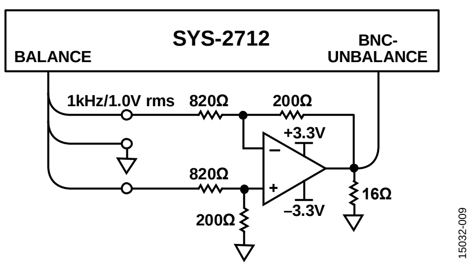

Figure 9. THD + N Test with 16 Ω Load

THD + N VS. V_{OUT}/I_{OUT} RESULT

Figure 10 and Figure 11 depicts THD + N vs. V_{OUT}/I_{OUT} of the recommended operational amplifiers.

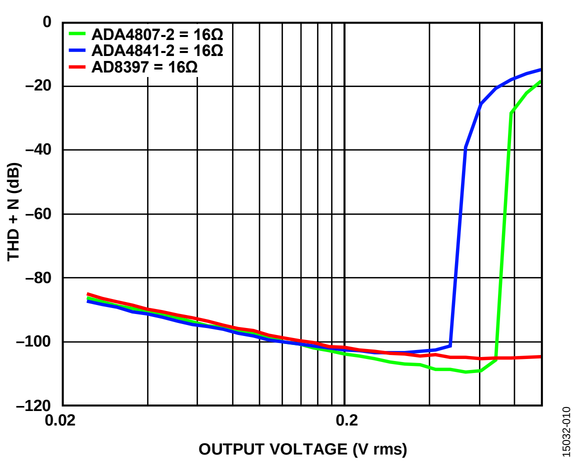

Figure 10. THD+N vs. V_{OUT} of the ADA4841-2, ADA4807-2, and AD8397

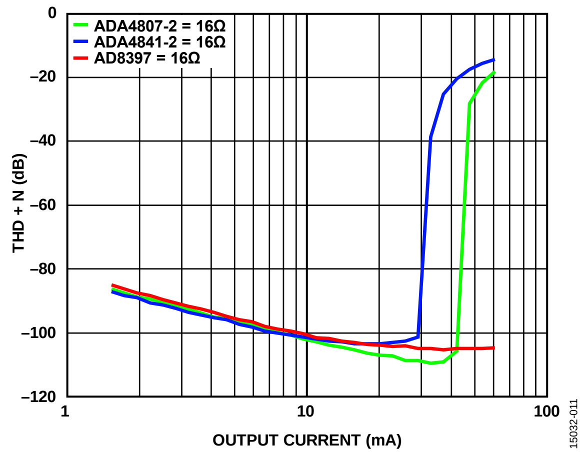

Figure 11. THD+N vs. I_{OUT} of the ADA4841-2, ADA4807-2, and AD8397

Table 2 details the maximum current and maximum output power with parameters set at <−100 dB THD + N at 16 Ω load. Figure 11 shows the following results:

- THD + N degrades dramatically when I_{OUT} reaches a certain current threshold.
- The AD8397 has high current drive capabilities at 16 Ω load.
- The ADA4807-2 maximum output current is 42 mA with only 1.2 mA I_Q, which is recommended when prioritizing the power consumption budget.

In most cases, 2 mW output power is enough to drive the headphones. THD + N, in this case, is important; as detailed in Table 2, THD + N at 2 mW of all recommended operational amplifiers is <−100 dB.

Table 2. Maximum Current and Output Power at 16 Ω Load

Parameter	ADA4841-2	ADA4807-2	AD8397
Maximum Current at <−100 dB THD + N	29.1 mA	42.1 mA	125 mA
Output Power at <−10 dB THD + N	13.6 mW	28.4 mW	250 mW
THD + N at 2 mW Output Power	−102.7 dB	−102.7 dB	−101.4 dB

DESIGN GUIDELINES

Resistance measured at 1 kΩ induces 4 nV/√Hz noise, which is more than the voltage noise of most operational amplifiers. In the circuit, the resistance of the resistors must be chosen carefully and must not exceed 1 kΩ.

Shielding is very important in mobile phones. To reach <−100 dB THD + N specifications, the tiniest of interferences can degrade THD + N performance, particularly when listening to music and browsing the internet simultaneously. Metal shielding can help prevent performance degradation.

For better heat dissipation, solder the exposed pad of the LFCSP package to the board pad and connect it to a big solid copper plane at the opposite side of the board by vias. The copper plane can be the ground or power plane of the board, but consult the ADA4841-2, ADA4807-2, and AD8397 data sheets to specify which plane to use.

Use a low dropout regulator (LDO) as the power supply of operational amplifiers. Place the decoupling capacitors (0.1 µF and 4.7 µF) near the operational amplifier power pins.

The capacitors in the audio path must be an NP0 ceramic type, as they offer better distortion performance. Use thin film resistors for optimum THD performance. Metal film resistors are also suitable, but typically cost more.

SUMMARY

Table 3 lists the different solutions and different considerations for voltage output DAC or current output DAC.

There are many things to consider when creating an excellent product. In real applications, according to different conditions (for example, power supply, targeted load resistance, power consumption budget, and expected performance), customers can choose the right solution and design the circuit to achieve personal expectations.

Table 3. Recommended Different Solutions

		DAC Current Output	
Parameter	**DAC Voltage Output**	**I to V Stage**	**Output Stage**
Low Cost	ADA4841-2	ADA4841-2	ADA4841-2
High Performance	AD8397	ADA4807-2, ADA4896-2, ADA4075-2	AD8397
Quality Performance by Low Power Consumption	ADA4807-2	ADA4807-2, ADA4896-2, ADA4075-2	ADA4807-2