

Application of Rail-to-Rail Operational Amplifiers

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ABSTRACT

This application report assists design engineers to understand the functionality and benefits of rail-to-rail operational amplifiers. It shows simplified schematics, functions, and characteristics of the output and input stages. Typical application schematics for rail-to-rail operational amplifier are also discussed.

Contents

Introduction	2
Dynamic Range and SNR in Low Single Supply Systems	2
The Output Stage	3
Construction of a Rail-to-Rail Output Stage	3
The Dependence of Output Signal Load	5
Slew Rate	7
Summary of Output Stage	7
The Input Stage	7
Construction of a Standard Input Stage	8
Construction of a Rail-to-Rail Input Stage	9
Summary of the Input Stage	11
Circuits Which Use the Rail-to-Rail Characteristics	12
Unity Gain Amplifier	12
Measurement of the Supply Current	12
Differential Amplifier With Rail-to-Rail Output	13
5-VPP Square Wave Oscillator Up to 600 kHz	13
Digital-to-Analog Converter With a Rail-to-Rail Output as an Adjustable Reference Voltage Source	14
Summary	14
References	15

List of Figures

1 Rail-to-Rail Output Stage	3
2 Output Stage of a TLC227x	3
3 Output Drive Capability	4
4 A_{VD} Dependent on the Load for TLV246x	5
5 Output Signal TLV2462 With 100- Ω Load to Ground	6
6 Output Signal TLV2462 With 100- Ω Load to $V_{DD}/2$	6
7 Inverting Amplifier	7
8 Change From Noninverting Amplifier to Buffer	8
9 Differential Amplifier	9

10	Rail-to-Rail Input Stage	9
11	Input Bias Current	10
12	Input Offset Voltage	10
13	Minimizing the Transient Distortions (THD)	11
14	Unity Gain Amplifier	12
15	Current to Voltage Converter	12
16	Instrument Amplifier With Two Operational Amplifiers	13
17	100-kHz Square Wave Oscillator With 5 V _{PP}	13
18	5-V Digital-to-Analog Converter With 0 to 5-V Output	14

Introduction

Electrical applications increasingly use a single supply voltage of 5 V or less as portable electrical equipment becomes more popular. The supply voltage for portable systems can be as low as the voltage provided by one battery cell (1.5 V). Reduced supply voltage designs must use the complete power supply span to have a usable dynamic range. Operational amplifiers that use the complete span between negative and positive supply voltage for signal conditioning are generally known as rail-to-rail amplifiers. The usable span is an important value because it influences several parameters such as noise susceptibility, signal-to-noise ratio (SNR), and dynamic range. Signal sources are often connected to the positive or negative supply rail. Operational amplifiers need rail-to-rail input capability to match both signal sources with one device. This report explains the function and the use of rail-to-rail operational amplifiers.

Dynamic Range and SNR in Low Single Supply Systems

Reducing the operating supply voltage from a ± 15 -V split supply to a single 5-V supply significantly reduces the maximum available dynamic range. The dynamic range at the output is determined by the ratio of the largest output voltage to the smallest output voltage. An industry standard operational amplifier like the TLC271 is specified at 5-V single supply with 3.8 V_{pp} for the maximum output swing. This means that the whole supply span can not be used for the output swing, resulting in a further reduction of the maximum available dynamic range and SNR. A rail-to-rail operational amplifier like the TLV24xx family can use the full span of the supply range for signal conditioning at the input and output.

Operational amplifier disturbance levels are independent of the supply voltage. This results in smaller spacing between usable and noise signals. If the operational amplifier is used with ac signals, by decoupling the signals from dc, then noise forms the determining disturbance signal. For a standard operational amplifier such as the TLC271C, the input noise voltage V_n at a signal bandwidth of 1 MHz equals $68 \mu\text{V}^\dagger = 68 \text{ nV}/\sqrt{\text{Hz}} \cdot \sqrt{1 \text{ MHz}}$. With a 5-V single supply, the reduced output range allows a maximum signal level of 3.8 V_{pp}. This results in a unity gain configuration in a SNR of 95.4 dB = $20 \log(4 \text{ V}/68 \mu\text{V})$. In the same configuration, a rail-to-rail amplifier such as the TLV246xI with $V_n = 11 \text{ nV}/\sqrt{\text{Hz}}^\dagger$ and a maximum signal level of 5 V_{pp} at the input and output provides a signal-to-noise ratio of 113 dB = $20 \log(5 \text{ V}/11 \mu\text{V})$ at BW = 1 MHz.

In a precision system the operational amplifier must amplify the dc voltage level precisely. Errors in this area result from offset and gain problems. In a 5-V system with a constant common-mode voltage, the TLC271C has an input offset voltage V_{IO} of 1.1 mV[†]. This alone limits the dynamic range to 71 dB = $20 \log(3800/1.1)$ in a unity gain configuration. The TLV245x, however, with $V_{IO} = 20 \mu\text{V}^\dagger$ and the rail-to-rail characteristic has a significantly higher dynamic range of 108 dB = $20 \log(5000/0.02)$ in the same circuitry.

[†]Typical values at 5 V single supply and 25°C.

When signal-to-noise ratio and dynamic range are critical design parameters, rail-to-rail characteristics of the operational amplifier must ensure that these parameters are met.

The Output Stage

If the output swing from a standard operational amplifier is not large enough to fit the system requirement (for example the analog-to-digital-converter input range), then a rail-to-rail operational amplifier must be used. Operational amplifiers with rail-to-rail output stages achieve the maximum output signal swing in systems with low single-supply voltages. They can generate an output signal up to the supply rails. A large output voltage swing results in increased dynamic range. For example, Figure 1 shows the output signal of a TLV2462 with a 5-V_{pp} input signal. The TLV2462 with a 5-V single supply operates as a voltage follower and drives a load of 1 k Ω . The low 1-k Ω load results in a voltage drop of several mV, which is not visible in the diagram.

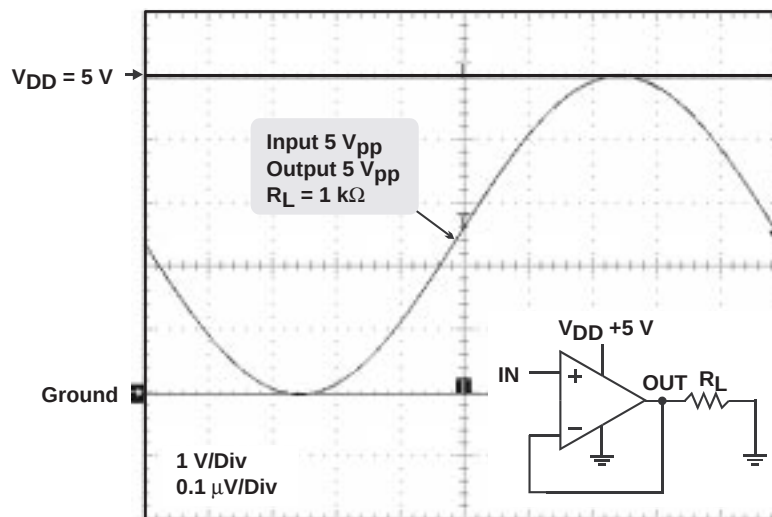


Figure 1. Rail-to-Rail Output Stage

Construction of a Rail-to-Rail Output Stage

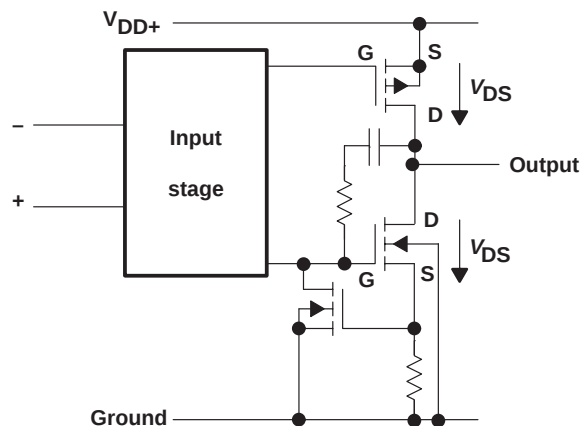


Figure 2. Output Stage of a TLC227x

The rail-to-rail characteristic is achieved by altering the output stage construction. Figure 2 shows the basic construction of a rail-to-rail CMOS output stage as used in the TLC227x. A complimentary MOS transistor pair, consisting of a self-locking P-channel and self-locking N-channel, forms the output. Both transistors operate as a common source circuit. A common source circuit functions like a common emitter circuit for bipolar transistors. Along with the current amplification, a voltage amplification also takes place. The voltage loss V_{DS} at the output stage transistors has a disadvantageous effect on the voltage gain. As the current increases through a MOS transistor the resistance between drain and source increases slightly. During high loading of the output, this resistance, together with the increased current, results in a higher voltage drop V_{DS} . The full output range of a rail-to-rail operational amplifier is therefore only useable with low load. Figure 3 shows this on the output level of the TLV243x and TLV246x.

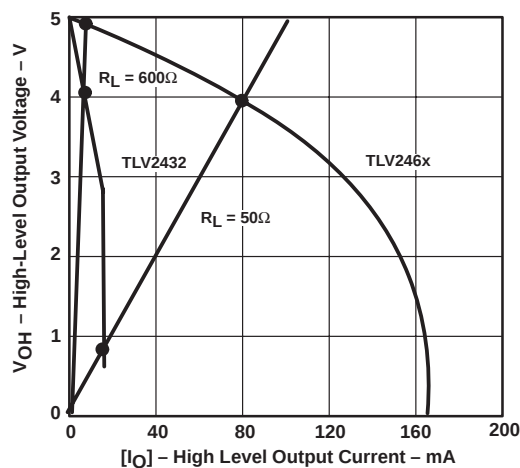


Figure 3. Output Drive Capability

Reduction of the output signal due to the load also results in a reduction of the open-loop gain A_{VD} . Because the open-loop gain is dependent on the connected load, the load should always be considered during comparison of the open-loop gain of different amplifiers. Figure 4 shows the influence of a resistive load on the amplification of a TLV246x.

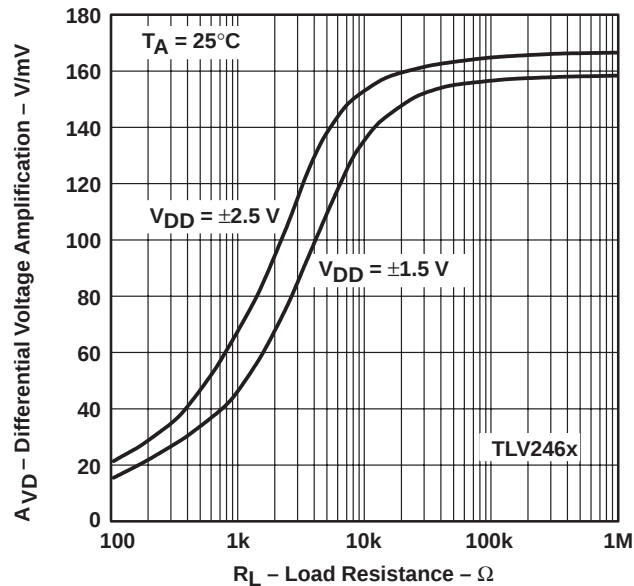


Figure 4. A_{VD} Dependent on the Load for TLV246x

The Dependence of Output Signal Load

It is important to know which potential the load is connected to when talking about the behaviour of the output signal due to the load. In applications with a single supply, it is typical for the load to be connected to ground (0V). The requirement from a rail-to-rail output is the capability to supply a load with current. Figure 5 shows an example of this on a TLV2462. The TLV2462 functions as a unity gain amplifier and drives a 100- Ω load against the supply ground. Because of the 600-mV voltage drop across the output transistor caused by the current, the output can only drive the signal up to a maximum voltage level of 4.4 V. The minimum voltage level however, reaches the 0 V of the ground level. At an output voltage of 0 V, no current flows through the load, since both ends of the load are at the same potential. With no current, there is no voltage drop across the output transistor. With a load driven against ground, an output signal limitation due to the load current only occurs at high voltage levels.

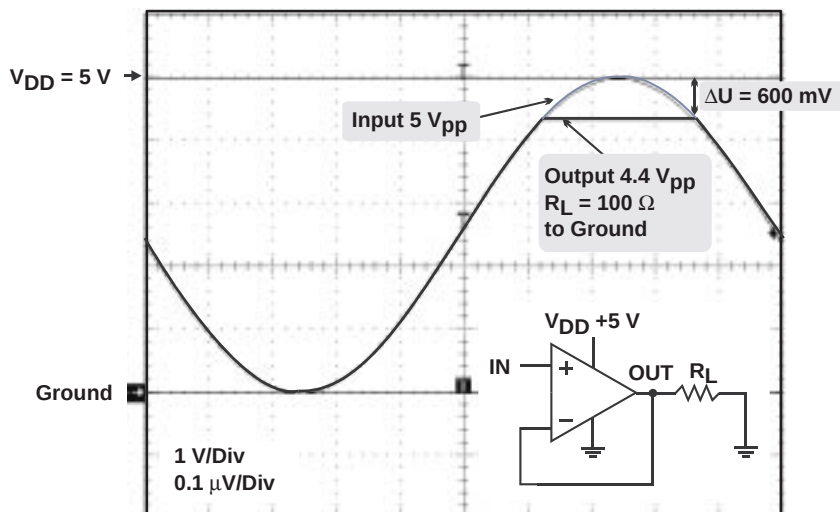


Figure 5. Output Signal TLV2462 With 100-Ω Load to Ground

A rail-to-rail output should not be limited to sourcing a load with current; it should also have the ability to sink a current. All rail-to-rail output stages of Texas Instruments have the capability of sourcing and sinking current. Figure 6 shows an example where the TLV2462 drives—as a unity amplifier—a load of 100 Ω against half the supply voltage $V_{DD}/2$. With a maximum input signal of 5 V_{pp} an output signal is produced as shown in Figure 6. In this case, at minimum and maximum voltage levels, the maximum current flows through the respective output transistor. The resulting voltage drop of 300 mV at the respective peak voltages restricts the output signal to 4.4 V_{pp}.

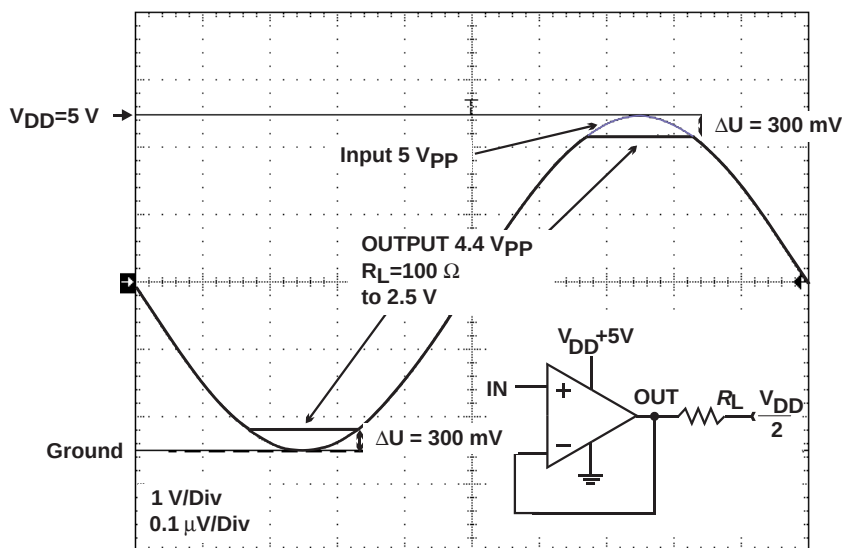


Figure 6. Output Signal TLV2462 With 100-Ω Load to $V_{DD}/2$

Slew Rate

Another important parameter, especially for ac application characteristics, is the slew rate of the output stage. The slew rate is a measure for the maximum possible voltage rise and fall speed, which is the ratio of the voltage change during a period of time. To reproduce a sine signal without distortion, use the following equation:

$$SR = 2\pi f_{\max} V_p \quad (1)$$

Equation 1 shows that if the output voltage is reduced by a lower supply voltage, the required slew rate decreases proportionally with the possible voltage level. This should be noted when comparing a CMOS rail-to-rail operational amplifier and a standard amplifier.

The standard amplifier with an output range of ± 13 V requires a slew rate of 82 V/ μ s to accurately reproduce a 1-MHz sine wave signal with 26 V_{pp}. A rail-to-rail amplifier with a 3-V single supply needs only a slew rate of 9.4 V/ μ s to achieve a distortion free 1-MHz sine wave signal with 3 V_{pp}. The slew rate also depends on the load and decreases with increasing load.

Summary of Output Stage

Rail-to-rail output quality is only comparable with another under identical load. Without a load on the output, it is possible for every rail-to-rail operational amplifier to bring the output signal up to the supply rail. A rail-to-rail output should be capable of both sourcing and sinking current in order to also drive loads not connected to ground. Operational amplifiers supplied with low supply voltages can only provide low signal amplitudes, which require a lower slew rate.

The Input Stage

In some applications an operational amplifier requires a rail-to-rail input in addition to the rail-to-rail output. The signal at the input pins must be in the input common-mode voltage range V_{ICR} to ensure the functionality of the amplifier. A rail-to-rail input stage offers a V_{ICR} that minimally includes the whole supply span. The V_{ICR} of the TLV246x extends beyond the supply rails by 200 mV for maximum dynamic range in low-voltage systems. A rail-to-rail input has advantages and disadvantages; it is not required in every application, but only in applications where the input signal is outside a standard common-mode range. Figure 7 shows a typical operational amplifier configured as an inverting amplifier. The relationship of the resistances R_F and R_G determine the gain in the circuit. R_C compensates offset errors from the input bias current.

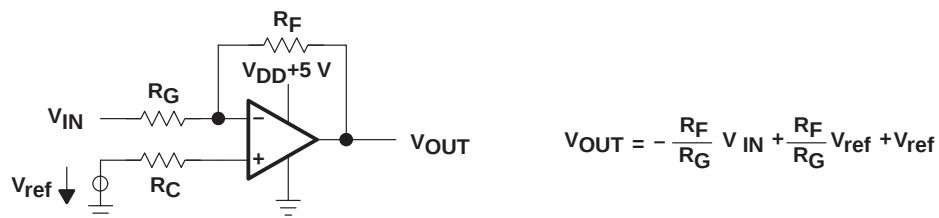


Figure 7. Inverting Amplifier

The noninverting input is connected to a fixed voltage level V_{ref} . The common-mode input voltage is maintained at a constant value, because the inverting input, via the feedback, takes the same reference potential as the noninverting input. In systems with a double supply, this is typically the circuit ground. In most cases it is half the supply voltage for single supply systems. The V_{ICR} of a standard operational amplifier in most cases contains this common-mode voltage level, mentioned above. If the reference level V_{ref} lies within this standard V_{ICR} , a circuit like that shown in Figure 7 does not necessarily require a rail-to-rail input stage.

The circuit shown in Figure 8 behaves differently. The inverting input here also follows the noninverting input via the feedback. In this case no fixed voltage level lies at the noninverting input, but the signal itself does. At high gains, the input signal is small and lies within the V_{ICR} of a standard operational amplifier. If the resistance R_G is removed, a unity gain amplifier, also called an impedance converter or voltage follower, is formed. This circuit produces a gain of 1 so that the input level is equal to the output level. If the entire output range of the rail-to-rail operational amplifier is used for signal conditioning, then a rail-to-rail input stage is also required. Impedance converters and high-side sensing applications are the main activity areas for operational amplifiers with rail-to-rail input and output.

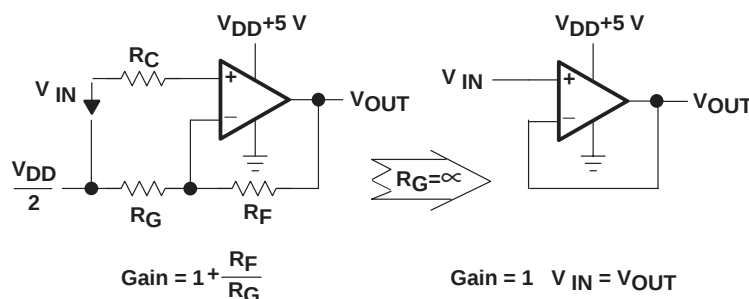


Figure 8. Change From Noninverting Amplifier to Buffer

Construction of a Standard Input Stage

On a standard operational amplifier using bipolar technology, the input differential amplifier, as shown in Figure 9, consists ideally of equal transistors. To achieve ground potential in the common-mode range, PNP transistors are primarily used here. Likewise in the MOS technology, P-channel transistors are used. There is a voltage drop of around 0.7 V across the PNP transistor and around 0.3 V across the bias current source. This results in a limited common-mode range, which always lies at least 1 V below the positive supply voltage. In the other direction, the V_{ICR} extends up to the negative supply voltage or slightly beyond. To enable use of the full supply voltage range, the construction of the standard differential amplifier has to be modified.

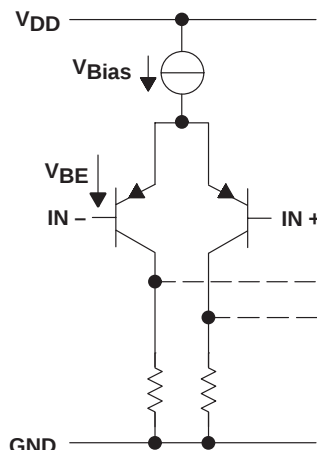


Figure 9. Differential Amplifier

Construction of a Rail-to-Rail Input Stage

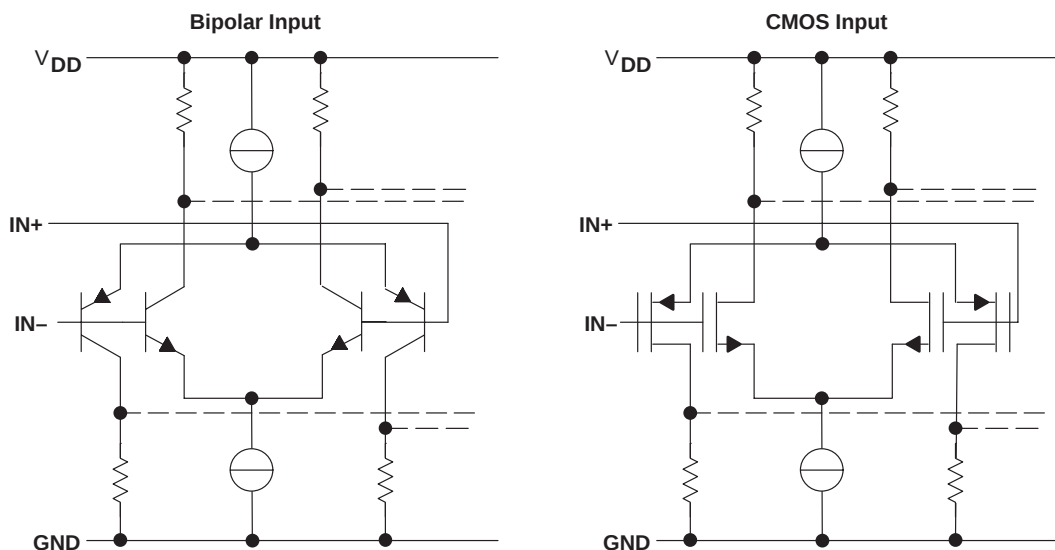


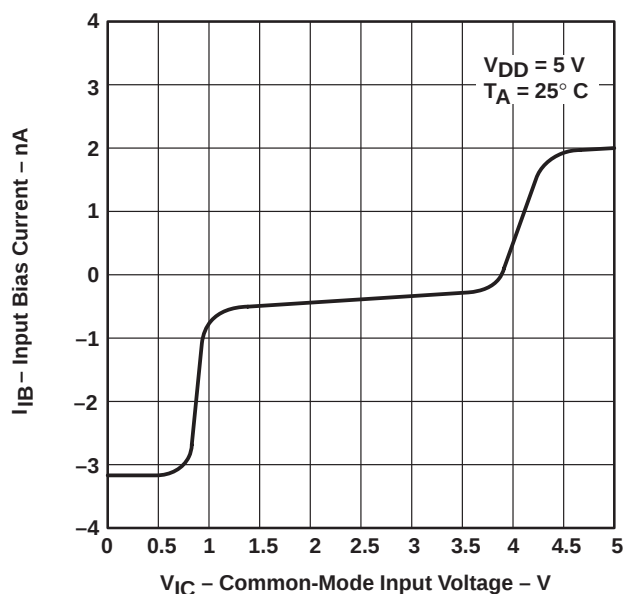
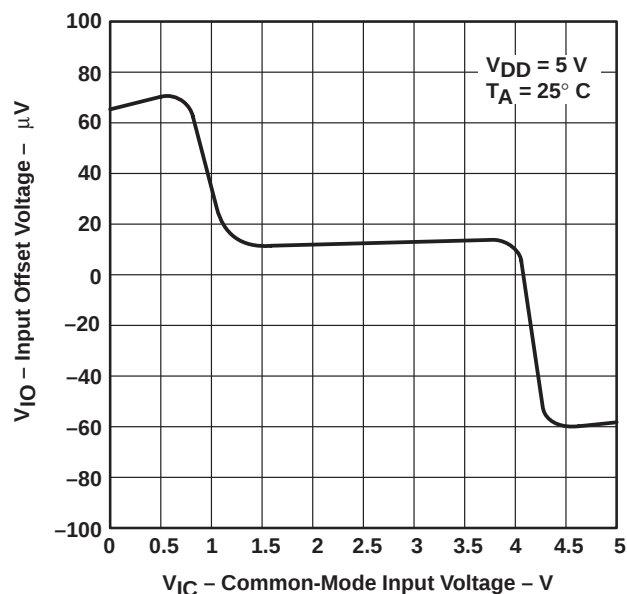
Figure 10. Rail-to-Rail Input Stage

There are various methods of constructing these types of input stages. Figure 10 shows the general construction of a rail-to-rail input stage using two different techniques. The bipolar input stage is used in the TLV245x and TLV246x. The input stage of the TLV247x series is designed in CMOS technology. The bipolar input stage in Figure 10 shows clearly that two differential amplifiers are being driven simultaneously. The differential amplifier with PNP transistors, mentioned before, works up to a maximum common-mode level of 1 V below the supply voltage. The differential amplifier working with NPN transistors requires a common-mode level of at least 1 V.

Table 1. The Different Common-Mode Input Ranges

COMMON-MODE INPUT RANGE WITH SINGLE SUPPLY VOLTAGE V_{DD}			
DIFFERENCE AMPLIFIER TYPE	MAXIMUM NEGATIVE INPUT VOLTAGE	MAXIMUM POSITIVE INPUT VOLTAGE	COMMON-MODE INPUT VOLTAGE RANGE
PNP	0 V	$V_{DD} - 1$ V	0 V to $(V_{DD} - 1)$ V
NPN	1 V	V_{DD}	1 V to V_{DD}
PNP+NPN	0 V	V_{DD}	0 V to V_{DD}

As shown in Table 1, there are three input ranges for a rail-to-rail input stage. In the input range from 0 V to around 1 V, only the PNP differential amplifier is active. From approximately 1 V to approximately $(V_{DD} - 1)$ V both input amplifiers are active. From around $(V_{DD} - 1)$ V up to V_{DD} only the NPN differential amplifier is active. Both differential amplifiers, according to the transistor type, have different polarity input bias currents I_{IB} . In the V_{ICR} where both NPN and PNP differential amplifiers are activated, these bias currents compensate themselves and form a bias current around 1000 times smaller than a standard bipolar input stage. The input offset voltage V_{IO} also changes in each range, which depends on the activated differential amplifier. Figure 11 and Figure 12 show these two values for the TLV245x series. This characteristic has the benefit that in the range from around 1 V to $(V_{DD} - 1)$ V the input stage has lower input bias in comparison with values for a standard bipolar input stage typical of this technology.

**Figure 11. Input Bias Current****Figure 12. Input Offset Voltage**

The different bias currents and offset voltages in Figure 11 and Figure 12 result in a different output error in each range. If the whole input range is used, distortion is generated at the transitions of the individual ranges. By connecting a series resistance R_C as shown in Figure 7 and Figure 8, it is possible to reduce the errors at the transitions caused by the bias currents. The required resistance is as follows:

$$R_C = \frac{R_G \times R_F}{R_G + R_F} \quad (2)$$

The bias current at the resistors now causes an equal voltage drop at both inputs. To minimize a voltage drop caused by the bias current, all resistance values must be kept as small as possible for the application. Typical values for R_C lie below 10 k Ω . This significantly reduces the transient distortions.

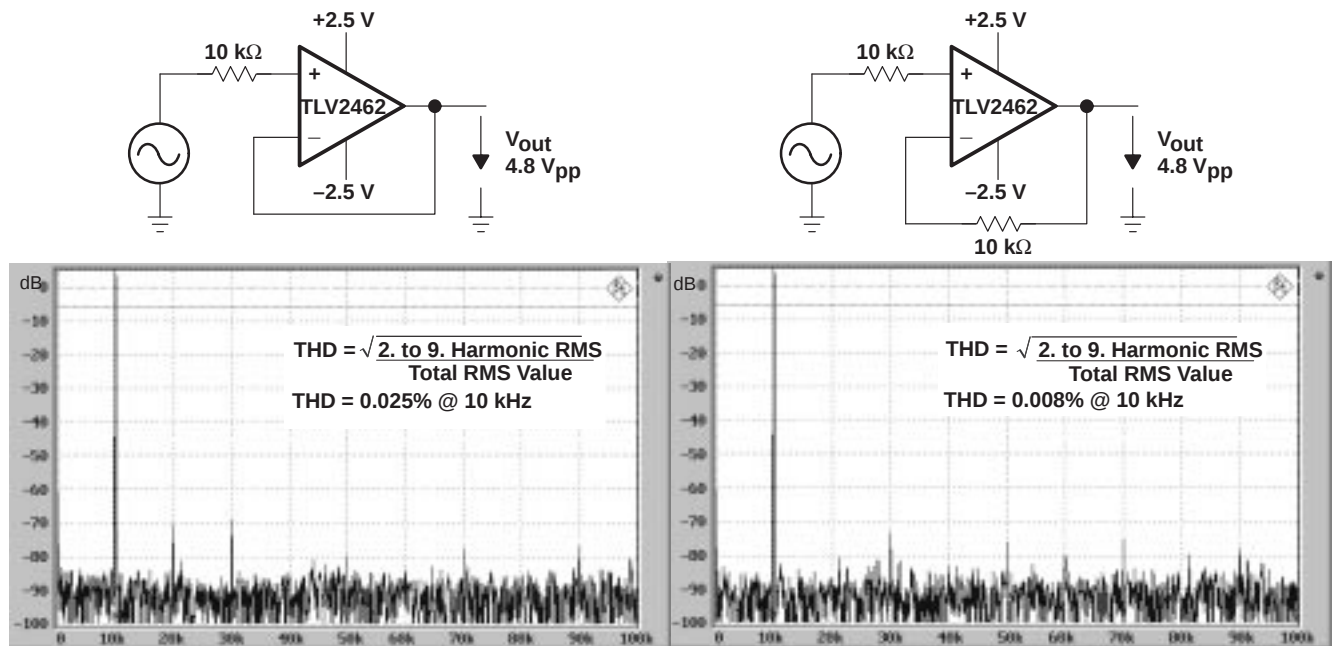


Figure 13. Minimizing the Transient Distortions (THD)

To emphasize the function of the compensation resistor, large resistance values of 10 k Ω have been deliberately selected for the circuit shown in Figure 13. Both noninverting amplifiers are set to a gain of 1. The left amplifier operates without a resistance in the feedback circuit. For compensation, both inputs on the right amplifier are connected with an equal resistance. This balances the voltage drops on both inputs, which are caused by the input currents. This reduces the total harmonic distortion (THD) from 0.025% to 0.008%.

Summary of the Input Stage

This section shows that a rail-to-rail input is not required in every application. In many cases, a standard input range, such as that of a TLC450x, is sufficient. The main advantage of a rail-to-rail input is the higher common-mode input range. It is possible to drive the amplifier in the entire common-mode input range from 0 V up to V_{DD} and above both rails. A disadvantage is the additional distortion caused by the transitions in the common-mode input range. The rail-to-rail input stage behaves like a normal standard input stage if the common-mode voltage is fixed or fits in one field of the common-mode input range.

Circuits Which Use the Rail-to-Rail Characteristics

The following circuits use the rail-to-rail benefits.

Unity Gain Amplifier

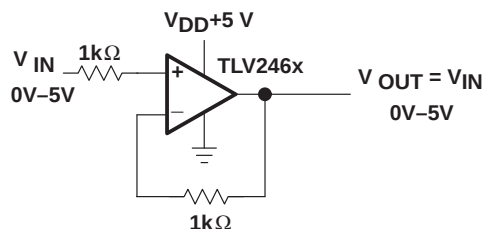


Figure 14. Unity Gain Amplifier

Figure 14 shows a buffer circuit. The rail-to-rail characteristic of the TLV246x makes the full operating voltage range of 0 to 5 V available for input and output signals. To reduce distortion both input resistors are used.

Measurement of the Supply Current

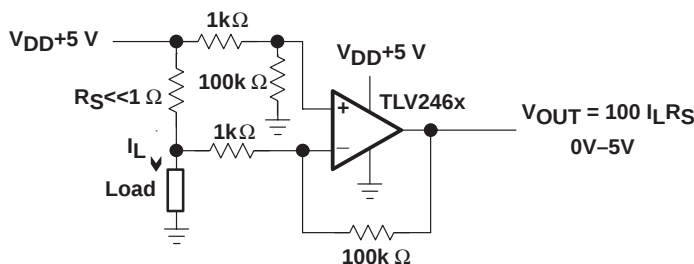


Figure 15. Current to Voltage Converter

The rail-to-rail input of the TLV246x in the circuit shown in Figure 15 allows measurement of the load current in a 5-V system. The load current through R_L is measured by applying the voltage drop across the shunt resistor R_S to the differential input. This input voltage is amplified 100 times. The rail-to-rail output allows output voltages, which extend up to the supply voltage, to be generated. The output voltage is proportional to the load current. Selecting an appropriate shunt resistor R_S for the circuit can set the maximum load current. R_S is therefore calculated as follows:

$$R_S = \frac{0.05 \text{ V}}{I_{L\text{max}}} \quad (3)$$

Differential Amplifier With Rail-to-Rail Output

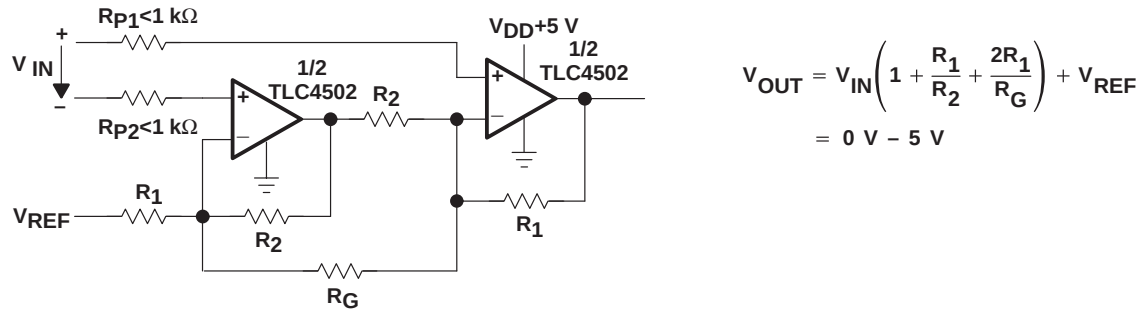


Figure 16. Instrument Amplifier With Two Operational Amplifiers

The TLC4502, with a typical common-mode rejection of 100 dB and a low temperature drift of $1 \mu\text{V}/^\circ\text{K}$, has outstanding characteristics for constructing an instrument amplifier, as shown in Figure 16. A high input impedance for the differential signal is achieved by using two operational amplifiers. The two resistors R_{P1} and R_{P2} provide protection against excessive input currents. The resistors R_1 and R_2 must have a tolerance of $\leq 0.1\%$ to achieve high common-mode rejection. The resistor R_G adjusts the gain of the entire differential amplifier. The rail-to-rail output signal is calculated using the following equation:

$$U_{OUT} = U_{IN} \left(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_G} \right) + U_{REF} \quad (4)$$

5-V_{pp} Square Wave Oscillator Up to 600 kHz

Figure 17 shows a 5-V square wave generator using the rail-to-rail amplifier TLV277x. The amplifier offers a rail-to-rail output and a slew rate of $10.5 \text{ V}/\mu\text{s}$. In this circuit, the TLV277x can deliver at the output a 5-V_{pp} square wave up to 600 kHz. The frequency is independent of the operating voltage. The output frequency depends on the value of the resistors and the capacitor. For changes of R and C the frequency up to 600 kHz is calculated using the following equation:

$$f \approx \frac{1}{0.00014(R \cdot C)^{0.3} + 1,4 R \cdot C} \text{ at } R > 20 \text{ k}\Omega \quad (5)$$

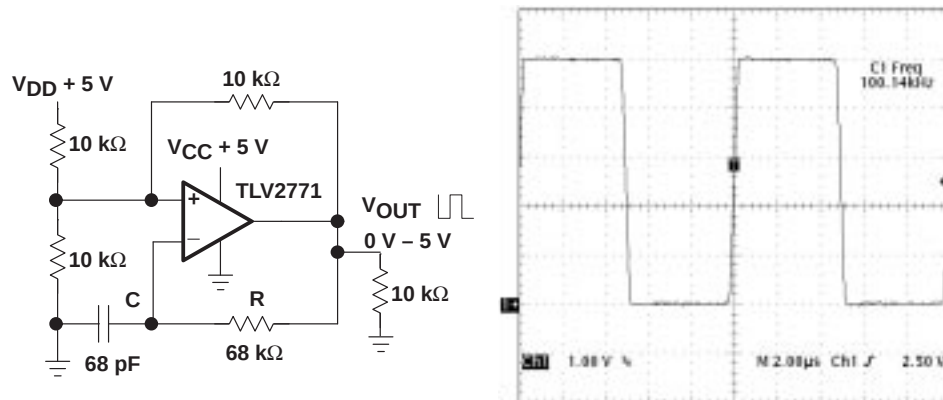


Figure 17. 100-kHz Square Wave Oscillator With 5 V_{pp}

Digital-to-Analog Converter With a Rail-to-Rail Output as an Adjustable Reference Voltage Source

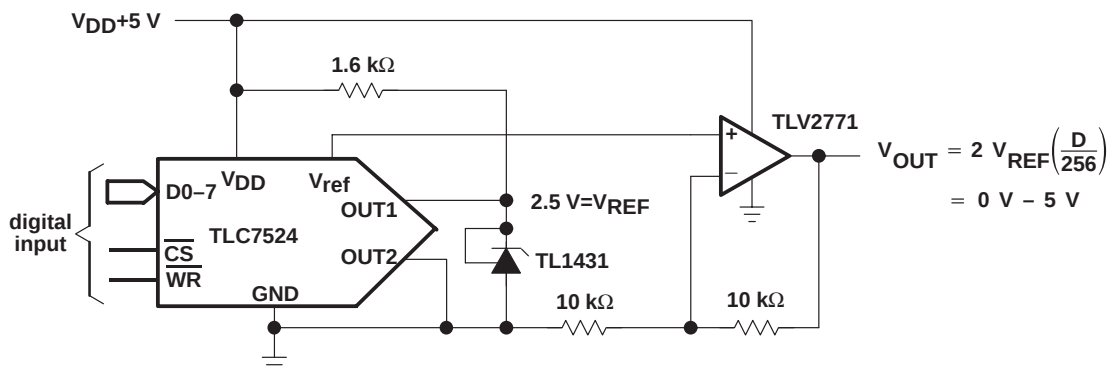


Figure 18. 5-V Digital-to-Analog Converter With 0 to 5-V Output

The combination of the digital-to-analog converter TLC7524 and the rail-to-rail operational amplifier TLV2771 shown in Figure 18, forms an 8-bit digital-to-analog converter powered by a single-voltage supply of 5 V. The TLV2771 can drive a 600- Ω load, which allows the converter to be used as a digitally adjustable reference voltage source for loads $\geq 600\ \Omega$.

The TLC7524 supplies a digitally-adjustable output voltage of $V_{REF} = D/256$. The reference voltage V_{REF} is generated with the TL1431 with an accuracy of 0.4 %. The TLV2771 works as an impedance converter with a gain of 2. The total output voltage of the circuit is calculated as follows:

$$V_{OUT} = 2 V_{REF} \left(\frac{D}{256} \right) \quad (6)$$

Summary

Single-supply systems with low voltage reduce the available signal range. Rail-to-rail amplifiers increase the signal level in such systems. Consequently, some parameters of a rail-to-rail amplifier, like the input noise voltage, offset voltage, and others become more important, which was shown in the first section. A rail-to-rail output stage is necessary to get an output swing up to the rails. It has been shown that such an output stage has a different structure that influences some parameters like the open loop gain and the slew rate, but it is also able to source and sink high currents. In some applications, like unity gain buffers or high-sensing in addition, a rail-to-rail input stage is needed if the whole supply range should be used for signal conditioning. It has been illustrated how a rail-to-rail input stage works and how it improves the input common mode range. Drawbacks have also been shown. Finally, the report shows some typical applications for rail-to-rail amplifiers.

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