How to use Rail-to-Rail Amplifiers to Improve Input Offset Accuracy

AN1683
Rev 0.00
Nov 2, 2011

In today's electronic systems, the negative power supply is disappearing, while the positive power supply voltage is decreasing. This trend is driving the proliferation of rail-to-rail amplifiers. While the supply voltage is changing, the signal level often remains the same.

For example, the standard video signal is 2V. When the power supply comes down to 2V, the amplifier/buffer must be linear or accurate within the full 2V supply range.

This application note focuses on the development of the rail-to-rail amplifier's input stage and discusses in detail the input enhancement circuit that overcomes the deficiencies associated with rail-to-rail amplifiers. For simplicity, this discussion is limited to MOSFET amplifiers.

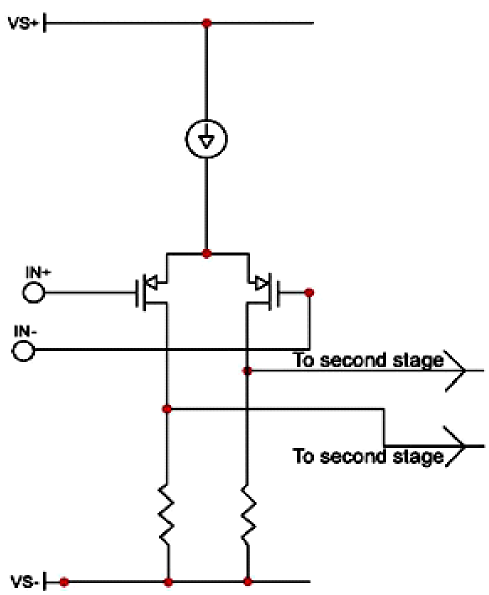

FIGURE 1. THIS TOPOLOGY PROVIDES DIFFERENTIAL GAIN AND REJECTS COMMON-MODE SIGNALS, BUT LIMITATION IS IN ITS OPERATING RANGE

The input stage from a basic op amp is shown in Figure 1. A transistor pair, called a differential pair, sits atop a current source to accommodate the differential input.

While this topology provides differential gain and rejects common-mode signals, its limitation is in its operating range. The input voltage range is 0-1.5V with a 3V single-supply. If the input voltage is raised above 1.5V, the current source is forced out of saturation. Once the current source leaves the saturation region, the gain is distorted.

EKG Application Example

For a sample application, such as current or voltage sensing by an electrocardiogram (EKG), the quality of the design is directly related to the voltage range of signals that can be processed. A standard textbook rail-to-rail op amp topology accommodates this challenge with a dual-input stage (Figure 2).

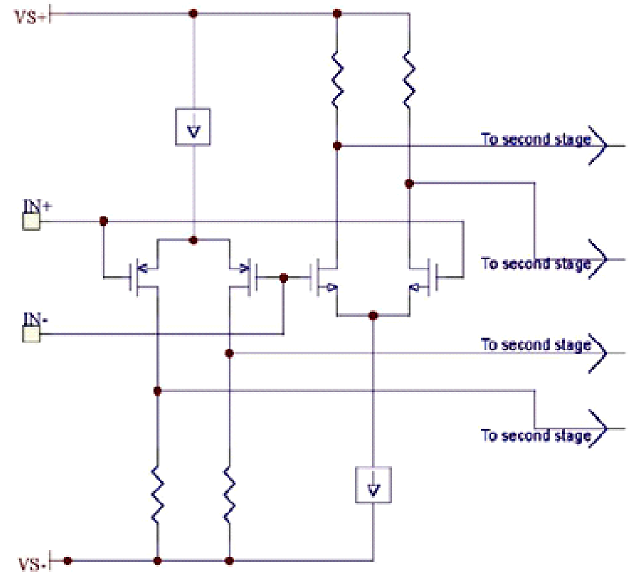

FIGURE 2. IN SENSITIVE APPLICATIONS LIKE THE EKG, ANY VARIATION IN OFFSET VOLTAGE JEOPARDIZES THE ACCURACY OF THE SYSTEM

When the input voltage approaches the lower supply rail, the PMOS transistor pair amplifies the signal. Conversely, the NMOS differential pair amplifies input signals that approach the upper supply rail. In this way, the input can span the entire supply voltage range. The most obvious trade-off to achieve this improvement in input range is the extra power required to bias the complementary differential pair.

A less obvious trade-off exists in the offset voltage with respect to the input bias voltage. The offset for the NMOS pair does not necessarily match the offset of the PMOS pair and occurs with opposing polarity.

Somewhere near mid-supply, there is a hand-off from one pair to the other. During the hand-off, the offset voltage is the average of the offset from each pair. This creates a stair-step characteristic, as shown in Figure 4.

For added insight, the offset is plotted for various temperatures. The PMOS input pair, active for low common-mode input voltages, exhibits a wide range of offset voltage vs. temperature. The variation in the NMOS pair causes the distribution on the right side of the plot for high common mode input voltages.

In sensitive applications like the EKG, any variation in offset voltage jeopardizes the accuracy of the system. The signal must first be amplified well beyond the offset voltage level to take advantage of rail-to-rail amplifiers with an input topology shown in Figure 2.

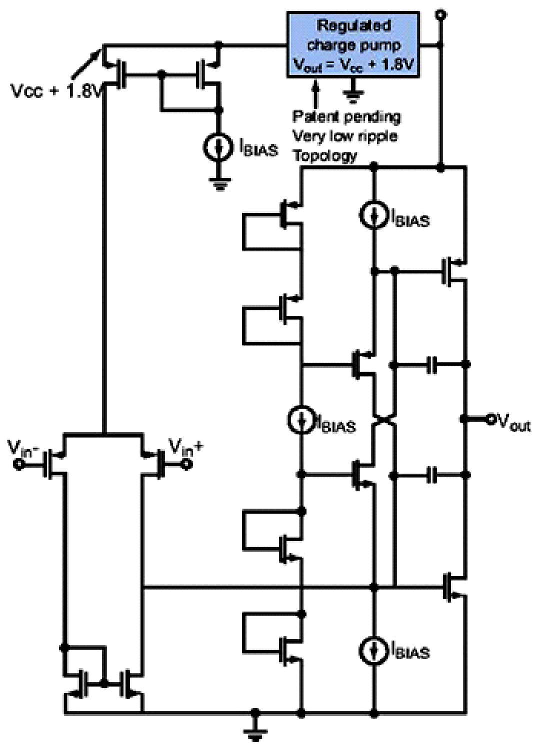

FIGURE 3. AN INPUT-RANGE ENHANCEMENT CIRCUIT HAS BEEN INCLUDED IN OP AMPS LIKE THE EL8178 TO ADJUST THE BIAS INTERNALLY PROVIDED TO THE CURRENT SORUCE

Full Range of Inputs

In precision and low-power applications, a new type of rail-to-rail amplifier is needed. The goal is to achieve a full range of input voltages without the crossover distortion in the offset voltage that occurs during the hand-off region of the dual differential design.

Let's return to the single differential design. The input range of the topology in Figure 1 does not allow for full range input operation.

A portion of the input range is preserved for biasing the current source in the saturation region. Can the biasing for the current source be accomplished in a manner that allows the input to span between the supply rails? An input-range enhancement circuit has been included in op amps like the EL8178 to adjust the bias internally provided to the current source (Figure 3).

Inside the enhancement circuit is a charge pump. While the mention of a charge pump usually brings up noise issues, the charge pump's operating frequency is beyond the bandwidth of the amplifier. Thus, there is no measurable change in the noise performance of the amplifier. Moreover, we must revisit the issue of offset voltage.

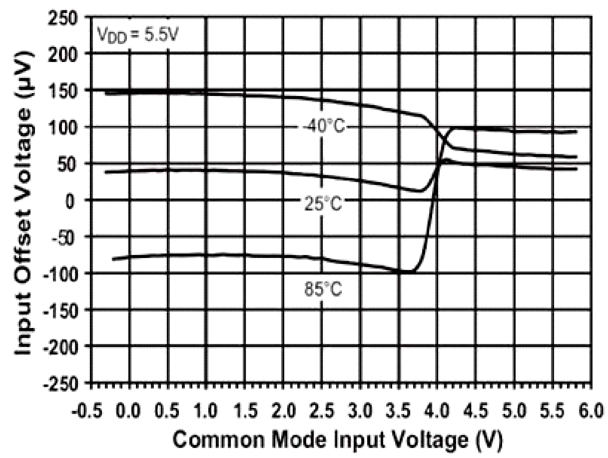

FIGURE 4. THE INPUT RANGE ENHANCEMENT CIRCUIT ALLOWS A SINGLE DIFFERENTIAL PAIR TO PROVIDE RAIL-TO-RAIL OPERATION WITHOUT THE NEED FOR A SECOND COMPLIMENTARY DIFFERENTIAL PAIR

Figure 3 fulfills our goal of maintaining the offset voltage. The input range enhancement circuit allows a single differential pair to provide rail-to-rail operation without the need for a second, complementary differential pair.

The offset voltage is completely dependent on the mismatch of only one set of transistors, so there is no crossover region. Careful layout and trimming can ensure that the input-referred offset voltage is less than 100 microvolts.

So far, the discussion has been limited to MOSFET implementations. Bipolar technologies can also benefit from this configuration. Besides improvement in offset voltage, a bipolar version would also exhibit a similar improvement in input bias current. The input bias current would feed only one matched differential pair, not two pairs with a crossover region.

Amp Evolution

An example of the evolution of rail-to-rail amplifiers is shown in Table 1. It summarizes the performance of three op-amp examples. The final version, the EL8178, provides the specifications needed by low power, high-resolution systems like a portable EKG machine.

TABLE 1. THE EL8178 PROVIDES THE SPECIFICATIONS NEEDED BY LOW-POWER, HIUGH-RESOLUTION SYSTEMS LIKE A PORTABLE EKG MACHINE

OP AMP INPUT TYPE (EXAMPLE)	INPUT STAGE	COMMON-MODE INPUT RANGE ON 5V SINGLE SUPPLY	OFFSET VOLTAGE (INPUT-REFERRED)
Basic (EL5144)	Single differential pair	0V to 3.5V	25mV
Rail-to-rail (EL5111)	Dual Differential Pair	-0.5V to 5.5V	3mV to 15mV
Biased rail-to-rail (EL8178)	Single differential pair with input enhancement	0V to 5V	50µV to 100µV

The basic input stage, which is composed of a single-differential pair, doesn't allow a full range of voltages at the input. A dual differential pair extends the input voltage range to the supplies, but suffers nonlinearity in the offset voltage (and input bias current in bipolar junction transistors) because of the hand-off between the two pairs. The third solution includes an internal enhancement to adjust the bias on the current source of a single differential pair to allow rail-to-rail operation with no discontinuity in offset voltage.

SALES OFFICES Renesas Electronics Corporation http://www.renesas.com

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Renesas Electronics America Inc.
1001 Murphy Ranch Road, Milpitas, CA 95035, U.S.A.
Tel: +1-408-432-8888, Fax: +1-408-434-5351

Renesas Electronics Canada Limited
9251 Yonge Street, Suite 8309 Richmond Hill, Ontario Canada L4C 9T3
Tel: +1-905-237-2004

Renesas Electronics Europe Limited
Dukes Meadow, Millboard Road, Bourne End, Buckinghamshire, SL8 5FH, U.K
Tel: +44-1628-651-700, Fax: +44-1628-651-804

Renesas Electronics Europe GmbH
Arcadiastrasse 10, 40472 Düsseldorf, Germany
Tel: +49-211-6503-0, Fax: +49-211-6503-1327

Renesas Electronics (China) Co., Ltd.
Room 1709 Quantum Plaza, No.27 ZhichunLu, Haidian District, Beijing, 100191 P. R. China
Tel: +86-10-8235-1155, Fax: +86-10-8235-7679

Renesas Electronics (Shanghai) Co., Ltd.
Unit 301, Tower A, Central Towers, 555 Langao Road, Putuo District, Shanghai, 200333 P. R. China
Tel: +86-21-2226-0888, Fax: +86-21-2226-0999

Renesas Electronics Hong Kong Limited
Unit 1601-1611, 16/F., Tower 2, Grand Century Place, 193 Prince Edward Road West, Mongkok, Kowloon, Hong Kong
Tel: +852-2265-6688, Fax: +852 2886-9022

Renesas Electronics Taiwan Co., Ltd.
13F, No. 363, Fu Shing North Road, Taipei 10543, Taiwan
Tel: +886-2-8175-9600, Fax: +886 2-8175-9670

Renesas Electronics Singapore Pte. Ltd.
80 Bendemeer Road, Unit #06-02 Hyflux Innovation Centre, Singapore 339949
Tel: +65-6213-0200, Fax: +65-6213-0300

Renesas Electronics Malaysia Sdn.Bhd.
Unit 1207, Block B, Menara Amcorp, Amcorp Trade Centre, No. 18, Jln Persiaran Barat, 46050 Petaling Jaya, Selangor Darul Ehsan, Malaysia
Tel: +60-3-7955-9390, Fax: +60-3-7955-9510

Renesas Electronics India Pvt. Ltd.
No.777C, 100 Feet Road, HAL 2nd Stage, Indiranagar, Bangalore 560 038, India
Tel: +91-80-67208700, Fax: +91-80-67208777

Renesas Electronics Korea Co., Ltd.
17F, KAMCO Yangjae Tower, 262, Gangnam-daero, Gangnam-gu, Seoul, 06265 Korea
Tel: +82-2-558-3737, Fax: +82-2-558-5338

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