

## THE ACTIVE FEEDBACK AMPLIFIER - A VERSATILE ANALOG BUILDING BLOCK

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### INTRODUCTION

The Active-Feedback Amplifier (AFA) topology approaches the ideal Voltage-Controlled Voltage Source (VCVS) with distinct input and output common-mode levels. This topology is very useful whenever it is required to sense a differential voltage at the input whose common-mode level is different than at the output. With the AFA no ambiguity about the input and output grounds arises; compare this to op-amp based applications where one always has to decide where the 'ground' should be referenced too - input or output? Furthermore, when the op-amp is viewed as an integrator and not as an infinite-gain, infinite bandwidth block, then at frequencies not too remote from the unity-gain frequency the op-amp will be nothing like the infinite-gain block it is supposed to be. The AFA in contrast provides accurate performance right up to its unity-gain frequency. This paper explains these benefits.

### THE ACTIVE FEEDBACK AMPLIFIER

The topology of the Active-Feedback Amplifier (AFA) is also known as a:

- Differential Difference Amplifier
- Video Difference Amplifier
- Wideband Instrumentation Amplifier
- Indirect Current Feedback Instrumentation Amplifier,

depending on the particular implementation and who wrote the paper. We decided to call this topology the AFA, because the feedback is applied through an *ACTIVE* feedback path. The AFA is a much more universal analog building block compared to an op-amp since the AFA can be use with or without external components.

The active-feedback topology truly excels in the handling of differential signals on top of large common-mode signals. This of course can be done with the traditional three op-amp instrumentation amplifier, but not with such ease, signal processing speed, and high common-mode rejection as is possible through the AFA architecture.

The idea is not new and has been published in various academic forums [1] as early as the 1970s, and been used in other special ways, but general-purpose AFAs have been slow to reach the marketplace.

Only a few are offered commercially at the moment [2]. The underlying reason may be that the op-amp is so deeply entrenched into the culture, and so widely

available in numerous highly-refined embodiments, that few users are willing to stray from such a well-trodden path.

The purpose of this paper is to provide convincing evidence that there are very tangible benefits to be enjoyed by taking those adventurous steps off the beaten track.

### 'Easy to Use, Versatile'

When asked "Why do you like op-amps?" most users respond quickly by noting that they are "Easy to use!" and "Versatile!". They are also very familiar and highly documented. Probably no other electronic gain element has been so widely developed, applied and written about. The traditional virtues of ease-of-use and versatility are no less true of the Active Feedback Amplifier, which requires no external components to realize a variety of functions. However, the AFA has not yet become well-known, and it will be some time before it will command the same confidence which users have in its more popular forerunners.

As mentionend already, the traditional op-amp fails to behave like an op-amp at signal frequencies not too remote from the unity-gain frequency, and here is where the Active-Feedback Amplifier (AFA) offers some outstanding advantages in the area of *voltage-mode signal processing*. It should be noted though that some of the techniques used in the design of the AFA are also used in specialty op-amps, but even those are still constrained by the ambiguity of deciding where 'ground' should be referenced. The AFA introduces another degree of freedom compared to an op-amp by allowing the output ground potential to be chosen as freely as the input ground potential.

One of the authors has been a strong advocate of active feedback amplifiers for many years, and first used the principle in 1974 as a means to improve the linearity, and also increase the versatility, of the industry-standard analog multiplier, the AD534.

Figure 1 shows the basic concept, illustrated here in the most general terms. Two nominally identical input stages accept differential voltage signals  $V_X = V_{X1} - V_{X2}$  and  $V_Y = V_{Y1} - V_{Y2}$ . These stages need not be linear, but it is presumed that they *exhibit identical monotonic responses* to the inputs up to some predetermined maximum voltage. Let their outputs be  $V_X$  and  $V_Y$ .

We are not concerned just yet with the form of these intermediate signals (they will eventually be currents, that is, we will use  $g_m$  stages).

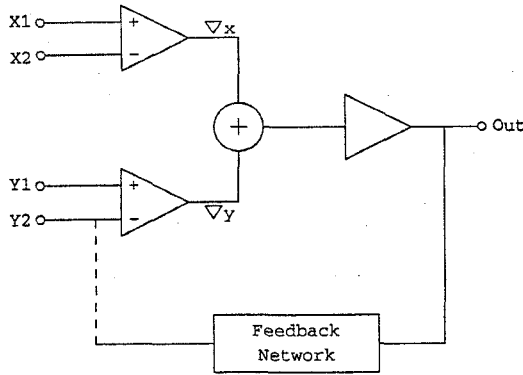


Figure 1 The Generalized Active Feedback Topology

In general terms

$$V_X = f(V_X) \quad \text{and} \quad V_Y = f(V_Y) \quad (1)$$

where 'f' is the same monotonic function of the instantaneous voltage. The outputs of these stages are then added and the sum  $V_X + V_Y$  applied to a 'high-gain' amplifier stage, which generates the output. (Assuming we will use  $g_m$  input stages, we may suspect that the output stage is actually going to be an integrator.)

When embedded in a suitable external network, the output amplifier forces a null at its (internal) input, requiring  $V_X = -V_Y$ . This in turn requires that

$$V_{Y2} - V_{Y1} = V_{X1} - V_{X2} \quad (2)$$

whatever the form of the function 'f'. Since it is not essential to precisely linearize the inputs stages, these can be relatively simple, and consequently very fast.

In a practical AFA, some care will in fact be taken to ensure that the input stages are sensibly linear. In this way, we can achieve low open-loop distortion, only finally using the slightly-nonlinear but exactly-matching feedback to very accurately linearize the overall transfer characteristic. Its basic structure is shown in Figure 2, from which it can be seen to approximate a high-slew-rate emitter-degenerated op-amp, but with two  $g_m$  stages. The output currents are summed at the emitters of the differential cascode stage, and with the help of the NPN mirror converted to a single-sided current which drives a grounded capacitor. All the voltage gain occurs at the node labeled 'TZ'. This voltage is finally buffered by a compound emitter-follower, shown here as '+1'.

The AFA could be used like any other op-amp, either by using both of the differential input ports connected in

parallel, or just one of these with the other inputs grounded, but there would be little advantage in so doing. All of the applications which we discuss below make advantageous use of the two input stages driven separately.

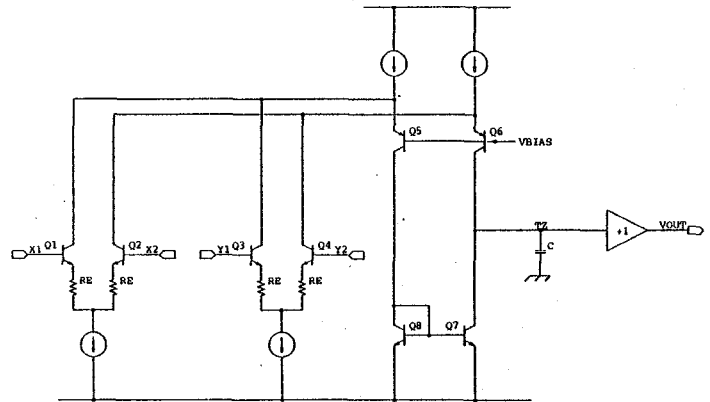


Figure 2 Basic Structure of the Active Feedback Amplifier

In all cases, the Y-input is used to close the feedback around the output stage. This has to do with the fact that in a practical AFA one of the  $g_m$  stages has to have a larger tail current to insure control even when the other input is clipping, this can be easily seen from Figure 2. When, for example, the X  $g_m$  stage is overdriven by pulling X1 much higher than X2, then the Y  $g_m$  stage has to compensate for the differential current of the X input to insure zero net current into the compensation capacitor at node TZ. If the Y  $g_m$  bias current were smaller than the X  $g_m$ 's, and if the Y  $g_m$  were used for feedback, it can never fully compensate the current coming from the X input and therefore the output will go to either rail depending on the polarity of the input. By making one of the inputs the designated feedback stage, this problem can be avoided.

A key feature of the AFA is that the effective  $g_m$ 's of the two input stages are closely matched. Thus, in applications providing differential-input gains of +1 or -1, or a single-sided gain of +2, the closed-loop gain is inherently accurate, without the use of any external resistors.

A useful model of a practical AFA is shown in Figure 3. The input stages are characterized by their  $g_m$ , but the use of the upper-case symbol  $G_M$  emphasizes that this is a large-signal property of the circuit (unlike a conventional op-amp, as we have seen) and is essentially independent of the instantaneous input voltage. The equivalent value of  $G_M$  is  $G_M = 1/2R_E$ , where  $R_E$  are the emitter degeneration resistors in Figure 2. This of course assumes that the transistor  $g_m$ s are much larger than  $1/R_E$ .

The resistance  $R_T$  represents the finite resistance of active devices associated with the 'TZ' node, and  $C_T$  is the total capacitance at this node. These components determine the transimpedance  $Z_T$  and thus the open-loop gain  $A(\omega)$  of the amplifier, and are shown connected to some general 'ground'.

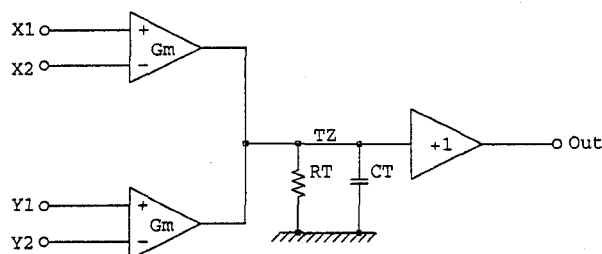


Figure 3 Model of the Active Feedback Amplifier

The open-loop DC gain from either input pair is simply  $G_M R_T$  (that is,  $R_T / 2R_E$ ). Since  $G_M = 1/2R_E$  is relatively small, the open-loop DC gain will be correspondingly low, typically 1000-2000. This, however, is not a detriment since for an integrator the key specification is the unity-gain frequency, NOT the DC open-loop gain. If the two input stages match perfectly, this finite open-loop gain will lower the closed loop gain (in the +1, -1, +2 modes) by about one part in 2000, that is, -0.05%. In practice, a further small gain error can be expected due to slight mismatches in the  $G_M$  of these stages.

The AC gain is dominated by the unity-gain frequency  $\omega_1 = G_M / C_T$ , just as in a conventional op-amp, except that *this is now maintained for both small and large inputs*. Thus, we should expect the differential gain and phase to be good. The capacitor  $C_T$  is actually formed by junction capacitances, and 'connects' not to an explicit ground pin, but indirectly to the positive and negative supply pins. In this respect, some of the same HF power-supply rejection problems as for an op-amp remain.

The junction capacitances forming  $C_T$  are voltage-dependent. This has two consequences. First, their absolute value becomes lower as the supply-voltages are increased, resulting in a higher value of  $\omega_1$  at  $V_S = \pm 15V$  than at  $\pm 5V$ . Second, they vary somewhat with the voltage at the 'TZ' node, which can lead to differential gain and phase errors. In this regard, some care has to be taken in the design of an AFA to ensure that to a first approximation the opposing voltage-nonlinearities in the capacitances of the PNP and NPN transistors tend to cancel. This is achieved by choice of device geometries.

The slew rate is high, being determined by the same  $I/C$  ratio as for the conventional op-amp, but now the bias

currents  $I$  can be much higher than before, since  $G_M$  is set predominantly by the resistors  $R_E$ . In fact, one can design the AFA so that it does not exhibit slew-rate limitations until the input stages go into clipping.

### Applications

The AFA can variously be thought of as a general-purpose wideband instrumentation amplifier, or as a differential-to-single-sided line receiver, or a simple unity-gain inverting amplifier, or a gain-of-2 cable driver (in either case without the halving of bandwidth suffered by an op-amp), or just a very good alternative to the op-amp in a wide variety of applications. Rather, we should say, an excellent alternative to 'op-amps', since in many cases the AFA performs tasks needing from three to five high-speed op-amps. From here on we use the AD830 as an instance of a practical AFA to illustrate some possible applications. For example, consider Figure 4, where we use a simplified representation of the IC for illustrating these applications.

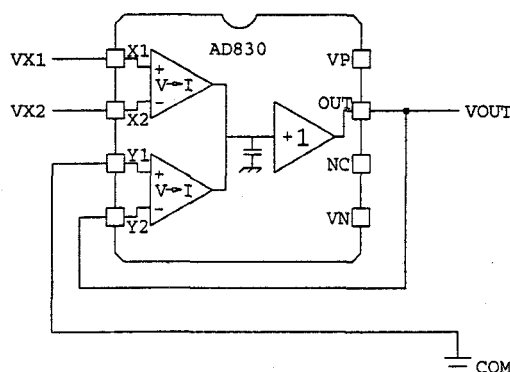


Figure 4 Basic Connections for the AD830

This looks disarmingly simple. Of course, as for any high-speed amplifier, it is prudent to include power-supply decoupling, but we will omit these components throughout this article only to emphasize the signal-path connections and the concepts. The data sheet should be consulted for full details in this respect.

The function performed here is

$$V_{OUT} (=V_{Y2}) = V_{X1} - V_{X2} \quad (3)$$

This indicates the ease with which an AFA can be used as a simple buffer amplifier of gain +1 or -1, where the gain depends only on the polarity of the input connection. The voltage at the Y1 pin determines exactly where the output voltage is referenced. This being the case, we can optionally use it as a voltage-following input, having the same bandwidth as the other two inputs, as shown in Figure 5.

Thus, within the one simple connection mode we have both a precision voltage-mode adder and voltage-mode subtractor.

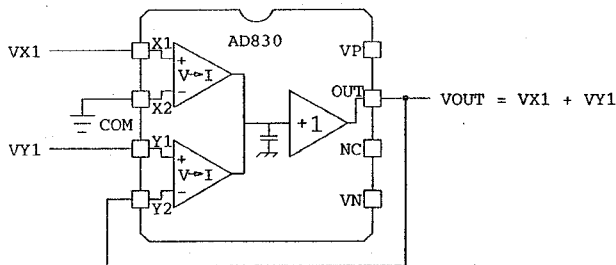


Figure 5 Use of the AFA as a Voltage-Summing Amplifier

Now consider what would be needed to fully equal this functionality (including the high-impedance inputs) using conventional op-amps. Figure 6 shows the connections. In addition to five op-amps, four closely-matched resistors are needed.

The exact function for the circuit in Figure 6 is

$$V_{OUT} = \left( \frac{R3+R4}{R1+R2} \right) \frac{R2}{R3} V_{X1} - \frac{R4}{R3} V_{X2} + \left( \frac{R3+R4}{R1+R2} \right) \frac{R1}{R3} V_{Y1} \quad (4)$$

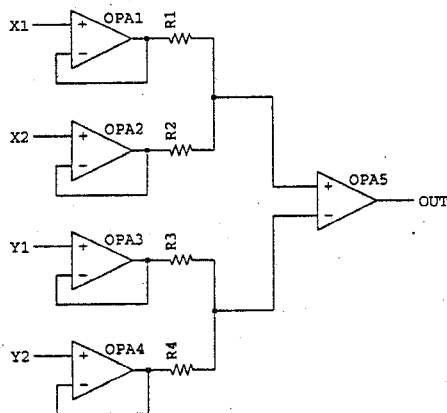


Figure 6 The Functional Equivalent of the AD830

Obviously, you, the user, are going to have to find resistors which match well enough to achieve both the required absolute gain accuracy and — usually much harder — the required common-mode rejection performance. By contrast, the AD830 specifications guarantee that the basic differential gain will be unity within  $\pm 0.2\%$ , and is typically much closer. The common-mode rejection performance of both its differential input stages is very good, as shown in Figure 7. Its DC value is typically 100dB. More importantly, it is still about 50dB at 10MHz; even the 1MHz value of 70dB would be extremely hard to achieve using the above circuit. Similar numbers can be observed for the LTC1193, the only other commercial AFA known to the authors.

REF LEVEL -10.000dB /DIV 10.000dB MARKER 100.000Hz MAG (UDF) -100.142dB

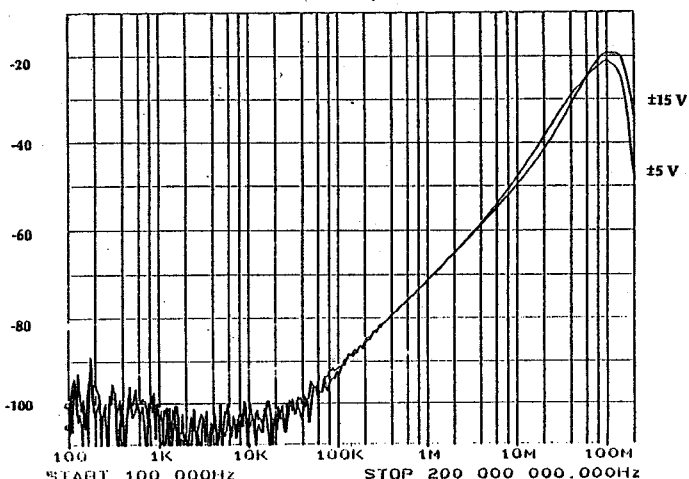


Figure 7 Common-Mode Rejection vs Frequency for the AD830

Less obvious is the fact that the overall bandwidth using traditional op-amps and the well-known form shown in Figure 6 will be only *one half* of their unity-gain frequency (assuming equal resistors) because OPA5 is operating at a 'noise gain' of two (always true of an op-amp inverter). Just the opposite situation can arise with the AD830 — we can *double* the gain without altering the bandwidth! And we don't need to change any external HF compensation components: none are required in the first place. Figure 8 shows the connections for this.

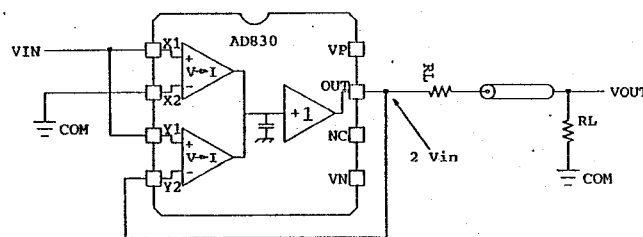


Figure 8 Using the AD830 at a Gain of +2 Results in No Loss of Bandwidth

In this case, inputs  $V_{X1}$  and  $V_{Y1}$  are driven from the same source; we are simply invoking the voltage-summing capability, using the one input signal 'twice'. However, since the HF response from either the X- or Y-input is identical there is no loss of bandwidth. We show here how this might be used to drive a reverse-terminated line, a typical application of a gain-of-two amplifier.

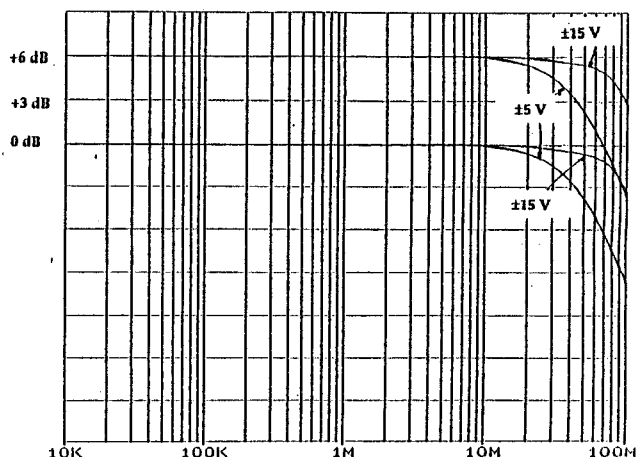


Figure 9 Comparison of the AC Response of AD830 at a Gain of +1 and +2

### Achieving Higher Voltage Gain

So far, we've seen the AD830 as an amplifier/buffer with a gain of -1, +1 and +2, without the need for external components. We've noted that while a conventional op-amp operating at a gain-of-two results in a halving of the -3dB bandwidth, the voltage-summing properties of the AD830 can be used to realize a gain of two without any reduction of bandwidth.

On the other hand, traditional methods of raising the closed loop gain can be used just as readily. It is only necessary to include a resistive voltage divider in the feedback path to  $V_{Y2}$ , as shown in Figure 10. The limit on the maximum available gain is set by the usual considerations of lowered bandwidth, increased noise and offset voltages and degraded gain accuracy due to the finite open-loop gain.

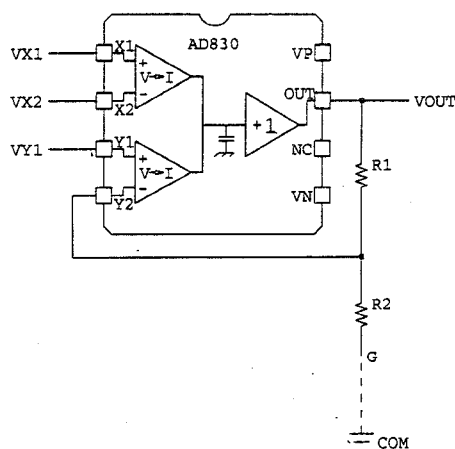


Figure 10 Using a Feedback Attenuator to Achieve Higher Gains

The most general input-output relationship for this circuit is

$$V_{OUT} = A_{CL} (V_{X1} - V_{X2} + V_{Y1}) \quad (5)$$

where the closed-loop DC gain  $A_{CL}$  is given by the usual formula

$$A_{CL} = \frac{R1 + R2}{R2}$$

It remains possible to apply a signal input to both  $V_{X1}$  and  $V_{Y1}$  inputs to double the gain without a further reduction of bandwidth. Also, a signal can optionally be applied to the bottom end of  $R2$  (node G); this signal will experience a gain of  $-R1/R2$ . Alternatively, if nodes G and  $V_{Y1}$  are connected, the gain from this composite node is +1.

Two other aspects of operation in this mode are worth mentioning. The first is to note that the distortion-canceling properties of the active feedback amplifier are in no way affected by the inclusion of the attenuator: the voltage at the two different input ports are still being forced into equality by the feedback, thus their residual nonlinearities still cancel. Second, the peak output voltage  $\pm V_{PK}$  is now larger than the approximately  $\pm 2.6V$  imposed by the clipping level of the input stages. The peak voltage is now the smaller of either  $\pm(V_S - 2V)$  or  $\pm 2.5V \cdot A_{CL}$ . Thus, for  $V_S = \pm 15V$  and  $A_{CL} = 2$ ,  $\pm V_{PK}$  would be  $\pm 5V$ , while it would be  $\pm 13V$  for  $A_{CL} \geq 5$ .

### Bipolar Voltage-to-Current Converter

As one last example of the AD830s many useful modes of operation, that of providing a bipolar output current at high impedance is shown in Figure 11. In this application the true power of having separate input and output common-mode inputs becomes apparent. The differential input voltage applied between inputs  $X1$  and  $X2$  will be replicated across  $R$  between  $Y2$  and  $Y1$ . The output common-mode signal in this circuit is the voltage defined by the load,  $Z_L$ , and  $I_{OUT}$ . As the output voltage varies, the output resistance is a factor of the common-mode rejection of the  $Y_{GM}$  stage and the resistor  $R$ .

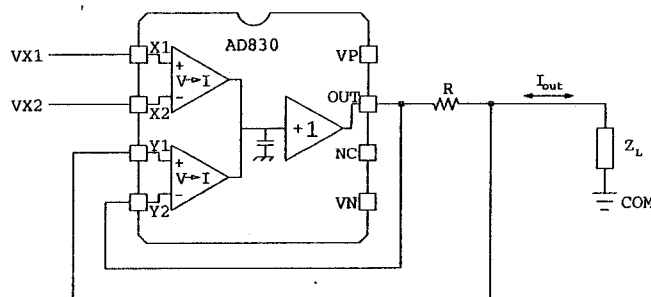


Figure 11 Precision Wideband Voltage-to-Current Converter

Using  $R = 1k\Omega$ , the scaling is simply 1mA per volt of input. The maximum current is limited to  $\pm 30mA$  by the output-current capabilities of the IC. The output resistance is determined by the common-mode rejection performance of the AD830. A CMRR of 60dB would result in an effective output resistance of  $1000 \cdot R$ . The output impedance at any frequency can be determined by consulting the CMRR curve provided in the data-sheet. The compliance range on the output is  $\pm(V_S - 2)$  reduced or increased by  $V_{IN}$ .

This circuit can be used as a differential-input integrator by simply making  $Z_L$  a capacitor. From this fundamental integrator building block various active-filter topologies can be realized; for example, using two such sections a biquad loop can be implemented.

#### SUMMARY: ACTIVE FEEDBACK AMPLIFIERS

For all wide band applications where moderate gains are required, or where differential-to-single-sided conversion is needed, or the summation of two voltages, the active feedback amplifier (AFA) is an excellent choice, particularly because of its high input impedance, high slew rate, good differential-gain and -phase behavior and its exceptionally high common-mode rejection performance in differential-to-single-sided modes. No resistors are needed to accurately achieve the useful gains of  $-1$ ,  $+1$  or  $+2$ . Unlike an op-amp, the bandwidth for gains of  $-1$  and  $+2$  is not halved. Higher gains can be achieved using the same feedback dividers as with an op-amp.

The harmonic distortion is low. At low frequencies, this is largely because of the cancellation of the residual non linearity of the two identical input  $G_M$  stages. At high frequencies, where the current in the compensation capacitor impairs this cancellation behavior, the distortion remains low because these highly degenerated input stages remain linear for large input voltages, unlike the  $g_m$  stage of a conventional op-amp, particularly one optimized for the highest possible DC gain.

The AD830, using a high-speed complementary bipolar (CB) process, is a good example of this form. Most notable is the deceptive simplicity with which many functions can be accomplished by the user. The high bandwidth of the AD830 allows it to be applied to a broad spectrum of contemporary needs. It can optionally be connected as a 'simple op-amp', using either one or both  $G_M$  stages, to provide either the nominal unity-gain frequency or twice that frequency.

Thus, the AFA performs all of the tasks normally accomplished by an op-amp, as well as many new ones. If one were to take any textbook showing a large number of op-amp applications, the AFA could be used in all of these except the most specialized, often with significant advantages in simplicity or performance.

On the other hand, this type of amplifier is not recommended where any of the following parameters are of critical concern: high open-loop DC gain; low input offset voltage; low input bias current; low voltage noise; low input bias-current noise; minimal power consumption. However, when using classical op-amps, be aware of the potentially adverse effects of external resistors, required to set the gain: these can also lead to a deterioration in one or more of the above parameters, particularly noise. And, as stressed in this article, use the unity-gain frequency,  $\omega_1$ , not the open-loop DC gain, in determining the amplifier's utility in high-speed applications. The AFA has exactly the same open-loop AC gain as an OPA having the same unity-gain frequency; in fact, connected in certain ways, it can actually have *twice* the  $\omega_1$ .

Lastly, it should be mentioned that the AFA idea can be extended to more than two inputs. In theory there are no limitations on how many additional  $G_M$  stages can be added, however, practical considerations will finally determine how many additional input stages can be accommodated.

#### [1] A few good references are:

- \* R. J. v. d. Plassche, "A wide-band monolithic instrumentation amplifier," *IEEE J. Solid-State Circuits*, vol. SC-10, no. 6, pp. 424-431, Dec. 1975.
- \* J. H. Huising, "Instrumentation amplifiers; A comparative study on behalf of monolithic integration," *IEEE Trans. Instrum. Meas.*, vol. IM-25, no.3, pp. 227-231, Sept. 1976.
- \* E. Säckinger and W. Guggenbühl, "A versatile building block; The CMOS differential difference amplifier," *IEEE J. Solid-State Circuits*, vol. SC-22, no. 2, pp. 287-294, Apr. 1987.
- \* B. J. v. d. Dool and J. Huising, "Indirect Current Feedback Instrumentation Amplifier with a Common-Mode Input Range that Includes the Negative Rail," *IEEE J. Solid-State Circuits*, vol. SC-28, no. 7, pp. 743-749, July 1993.

#### [2] Two examples are:

- \* AD830 from Analog Devices
- \* LTC1193 from Linear Technology

both are examples of the basic topology with two  $G_m$  stages, but differ in how the output amplifier is implemented.