THE CURRENT-FEEDBACK OTA

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ABSTRACT

The current-feedback OTA (CFB OTA) recently appeared in a new classification of operational amplifiers. It is dual to the operational floating amplifier (OFA), so all OFA circuits can readily be transposed into CFB OTA circuits. This paper discusses the theoretical basis of the CFB OTA, shows its relation to the OFA, and compares their performance in a simple V–I converter by showing how both can be built with the same two transistor stages. The advantages and disadvantages of the CFB-OTA implementation are discussed as well, but the main advantage of introducing the CFB OTA is that its introduction is virtually for free: most current opamps from the literature can be converted into CFB OTAs by re-wiring their input stage, without adding or re-sizing a single transistor.

1. INTRODUCTION

The current-feedback OTA recently appeared in a new classification of operational amplifiers [1, 2]. This classification is based on four-terminal theory instead of two-port theory, and thus contains nine instead of the four classes of operational amplifiers that appeared in earlier classifications (e.g. [3, 4]). Eight of these amplifier classes are well known, but the ninth seems to be new. The classification is briefly described in Section 2, where it is also explained why the name "current-feedback OTA" was given to the new device, although it is actually a current opamp with an additional voltage buffer.

This new device is dual to the operational floating amplifier (OFA) [5], which means that transposing a circuit containing OFAs will result in a circuit containing CFB OTAs. Thus many of the applications developed for the OFA can also be built using the CFB OTA. The main advantage of the CFB OTA is that almost no effort is needed to design it from a current opamp. Most current opamps can be used as CFB OTAs already, simply by using a circuit node that is normally connected to analogue ground as an additional voltage input, without adding a single transistor. On the other hand, to build an operational floating amplifier from a conventional opamp, the current flowing through the output transistors of the output buffer has to be mirrored and inverted, which means that two current-mirror stages have to be added. This does not mean, however, that the CFB OTA is less complex than the OFA; it rather means that current opamps are normally more complex than voltage opamps. This will be discussed further in Section 3.

A design example is presented in Section 4, where both the CFB OTA and the OFA are implemented using the same transistor stages connected in different order, and where the two amplifiers are used in a very simple application, a linear V–I converter circuit. The results show that the CFB-OTA circuit is much more linear (the input signal that produces 1 % THD is 10 dB higher), but also more noisy, such that its SNR at 1 % distortion is 2 dB better than that of the OFA circuit.

Most of this work was completed by the end of November 2000 when the author left the Signal and Information Processing Laboratory of the Swiss Federal Institute of Technology, Zürich, Switzerland.

CLASS	COMMON NAME
$\mathbb{V}$–$\mathbb{I}$	operational transconductance amplifier (OTA)
$\mathbb{V}$–$\mathbb{V}$	operational amplifier (opamp)
$\mathbb{V}$–$\mathbb{H}$	operational floating amplifier (OFA)
$\mathbb{I}$–$\mathbb{I}$	current-mode opamp
$\mathbb{I}$–$\mathbb{V}$	operational transresistance amplifier (OTRA)
$\mathbb{I}$–$\mathbb{H}$	floating OTRA
$\mathbb{H}$–$\mathbb{I}$	**current-feedback OTA (CFB OTA)**
$\mathbb{H}$–$\mathbb{V}$	current-feedback opamp (CFB opamp)
$\mathbb{H}$–$\mathbb{H}$	operational floating conveyor (OFC)

Table 1: Common names of the nine operational amplifiers.

2. DERIVATION OF THE CFB OTA

Earlier classifications of operational amplifiers (e.g. [3, 4]) started with the two-port equations of the universal active element,

$$\begin{bmatrix} v_a \\ i_\mathrm{a} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_b \\ -i_\mathrm{b} \end{bmatrix}, \tag{1}$$

and showed how these can be approximated with realisable two-ports. As a result, the classifications contain the four high-gain controlled sources with voltage and current inputs and outputs, written as $\mathbb{V}$–$\mathbb{V}$, $\mathbb{V}$–$\mathbb{I}$, $\mathbb{I}$–$\mathbb{V}$, and $\mathbb{I}$–$\mathbb{I}$ in this paper. The two terminals of each of the four stages ($\mathbb{V}$ and $\mathbb{I}$, input and output) always have the same impedance level: very high or very low. When four-terminal instead of two-port theory is used, as in [1, 2], then the two input terminals and the two output terminals are not seen as one port each, but as four independent terminals that can have different impedance levels. As a consequence, hybrid stages appear, namely a $\mathbb{H}$ input stage and a $\mathbb{H}$ output stage.

The $\mathbb{H}$ input stage, which has become well known through the CFB opamp, can also be understood as an extended $\mathbb{I}$ input stage whose analogue ground voltage is not fixed, but can be set through an additional terminal. The $\mathbb{V}$ output can also be extended to a hybrid stage. It copies the current flowing into the voltage output terminal to an additional current output terminal. This technique, which is called *output current sensing* or *supply current sensing*, has played an important role in the development of new opamps, e.g. the current-feedback opamp [6–8], or its extension, the operational floating conveyor (OFC, [9, 10]) which has both a $\mathbb{H}$ input and a $\mathbb{H}$ output.

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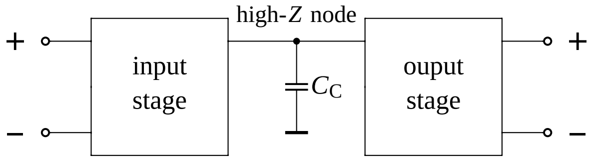

Figure 1: Block diagram of an operational amplifier.

As Table 1 shows, all operational amplifiers are already known, with the exception of the $\mathbb{H}$–$\mathbb{I}$ amplifier. We decided to call it current-feedback OTA (CFB OTA), although it is a current amplifier with an additional voltage input. The main idea behind this decision was to maintain the symmetry in the classification: the CFB OTA has the same relation to the OTA which the CFB opamp has to the opamp.

It should be mentioned here that the same functionality can also be described from a completely different theoretical background. One can show that the so-called infinite-gain second-generation current conveyor (CCII∞) from [11] is essentially the same as the CFB OTA. The background from which it came is, however, different, the CCII∞ was developed on the transistor level in order to optimise the trade-off between speed and distortion in current amplifiers. Thus both the theoretical concepts and the transistor implementations differ from what is discussed in this paper.

3. CFB OTA AND OFA

There is an important relation between the amplifiers in Table 1: duality. It was shown in [1] that the $\mathbb{V}$ input stage is dual to the $\mathbb{I}$ output stage, the $\mathbb{I}$ input stage is dual to the $\mathbb{V}$ output stage, and the $\mathbb{H}$ input stage is dual to the $\mathbb{H}$ output stage. This means, among other things, that the CFB OTA and the OFA are dual. Transposing a circuit containing OFAs will result in a circuit containing CFB OTAs, and vice versa. Thus all applications that were theoretically derived for the OFA (c.f. [5]) can be transposed into applications of the CFB OTA.

Both amplifiers are shown in Fig. 2. Without the feedback and the feedback resistor R, which will be explained in Sec. 4, the OFA is described by

$$i_1 = i_2 = 0, \quad v_3 = A_v (v_1 - v_2), \quad i_4 = -i_3, \quad A_v \to \infty, \tag{2}$$

and the CFB OTA is described by

$$i_1 = 0, \quad v_2 = v_1, \quad i_3 = -A_i\, i_2, \quad i_4 = A_i\, i_2, \quad A_i \to \infty. \tag{3}$$

(All currents are considered as positive when flowing into the amplifier terminals.)

All opamps are built as an input stage, a high-impedance point with an attached compensation capacitor, and an output stage, as shown in Fig. 1. The actual implementation of the high-impedance node may differ strongly from this simple view, c.f. [12], but this is not relevant for our comparison.

The $\mathbb{V}$ input stage of a conventional opamp feeds a current into the high-impedance point, and its $\mathbb{V}$ output stage copies the voltage from the high-impedance point to a single output. Thus its $\mathbb{V}$ input stage is an OTA, and its $\mathbb{V}$ output stage is a voltage buffer. To convert the opamp into an OFA, i.e. to convert this $\mathbb{V}$ output into a $\mathbb{H}$ output, an additional current-output terminal must be built that reproduces the current of the voltage output. As explained in [1, 5], this can be done either by sensing and replicating the supply current of the whole opamp, or by doing the same for the output branch of the opamp output voltage buffer. In both cases, two current-mirror stages must be added to the opamp circuit, since the current flowing into the current-output terminal and the current flowing into the voltage output terminal must add up to zero. Looking closely at the function performed by the $\mathbb{H}$ output stage, one finds that it may be seen as a second-generation current conveyor with negative unity gain (CCII−) [13].

The same can now be done for a current opamp. It has an $\mathbb{I}$ input stage, normally with only one input, and a $\mathbb{I}$ output stage. The $\mathbb{I}$ output stage converts the voltage at the high-impedance point into two balanced currents, thus it is an OTA, like the $\mathbb{V}$ input stage. The $\mathbb{I}$ input stage is only a current buffer that transfers the input current to the high-impedance node. Converting the $\mathbb{I}$ input stage into a $\mathbb{H}$ input stage means providing an additional voltage input through which the voltage at the current input can be set. Again, as with the $\mathbb{H}$ output stage, it appears that the $\mathbb{H}$ input stage performs the function of a CCII, but this time it does not matter whether its gain is positive or negative (this will be discussed again in the following section). Providing an additional voltage input to a current opamp is normally very easy. In many implementations of current opamps (e.g. [14]), the analogue ground voltage at the current input terminal is set by a voltage buffer whose input is connected to a reference voltage. Thus a current-mode opamp can be converted into a CFB OTA simply by using the input of this voltage buffer as an additional voltage input. This means, in other words, that structures implementing CFB OTAs have already been in use for a long time, they have just not been used in this way.

Note that a CFB OTA is generally not less complex than a floating opamp. The above discussion shows that it is more precise to say that every $\mathbb{I}$ input stage is a $\mathbb{H}$ input stage of which one terminal is wasted by connecting it to analogue ground instead of using it as a signal input. In other words, this means that current opamps are in general more complex than voltage opamps.

4. DESIGN EXAMPLES

The problem with giving a design example is to find an application that is so simple that it makes sense to implement it in a straightforward way, without specially modifying the amplifiers. Thus we have chosen a simple V–I converter in order to give an illustrative example.

Fig. 2 shows the V–I converter built with an OFA (converting v_1 to i_4) and with a CFB OTA (converting v_1 to i_3). The function of the OFA V–I converter is simply to buffer the voltage v_1 to v_2 using an opamp with high-gain feedback and then copy the current flowing through the resistor R to the terminal Z. The V–I converter built using the CFB OTA performs precisely the same function, but here the voltage copying is done by a simple voltage buffer. In the OFA circuit, the high-gain feedback makes the voltage difference between the two inputs very small, whereas in the CFB-OTA circuit, the feedback makes the current i_2 very small. Thus the OFA circuit will have the more accurate voltage transfer function from v_1 to v_2, while the CFB-OTA circuit will have better linearity, because the voltage buffer conducts only very little current. For the same reason, the output current noise of the voltage buffer will play a larger role in the CFB-OTA circuit than in the OFA circuit, so the CFB-OTA circuit will be noisier.

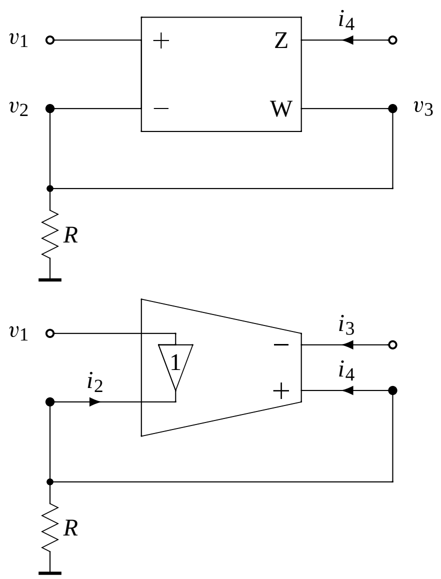

Figure 2: Linear voltage-to-current converter with OFA (top) and CFB OTA (bottom).

	nMOS	pMOS	
V_{T0}	0.85	−0.85	[V]
$\mu \cdot C_{ox}$	120	40	[μA/V^2]
γ	0.8	0.5	[$\sqrt{\mathrm{V}}$]
ϕ_0	0.94	0.91	[V]

Table 2: Typical threshold voltages, transconductance parameters, body factors, and characteristic potentials of the AMS 0.6 µm CMOS process.

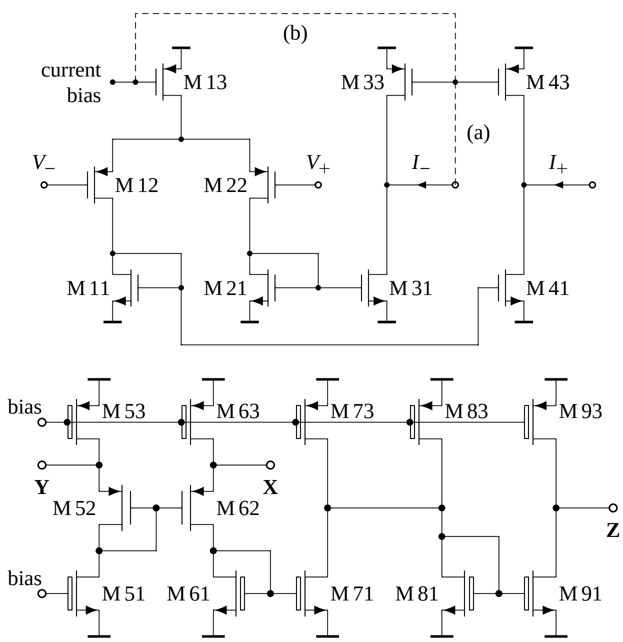

Figure 3: OTA (top) and CCII (bottom).

M 11, M 21, M 31, M 41	15 × 1.8 µm
M 12, M 22	600 × 0.6 µm
M 13	45 × 7.2 µm
M 33, M 43	45 × 1.8 µm
M 51	13.5 × 1.8 µm
M 52, M 62	600 × 0.6 µm
M 53, M 63, M 73, M 83, M 93	45 × 1.8 µm
M 61, M 71, M 81, M 91	15 × 1.8 µm

Table 3: Sizes of all transistors in the circuits.

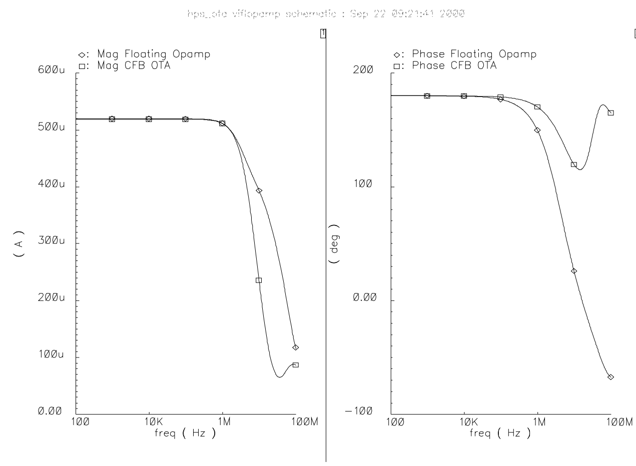

Figure 4: AC transfer function of both circuits.

We will now discuss implementations of both circuits using the AMS 0.6 µm CMOS process, whose main process parameters are shown in Table 2. Both amplifiers can be implemented using almost the same two stages. The top of Fig. 3 shows an OTA that can be used either as a single-output OTA when connection (a) is made or as a balanced-output OTA when connection (b) is made. Since we did not have to meet specific design criteria, we simply chose large transistors M 12 and M 22, a bias current of 40 µA, and a maximum drain-source voltage of 0.4 V for the current mirror transistors. The analogue ground was set to 1.2 V above the negative rail for a supply of 3.3 V to maximise the swing at the voltage inputs. The transistors of the current mirrors were made a bit longer for better matching, and the current source transistor of the differential pair was made even longer to provide a higher resistance. The resulting transistor sizes can be found in Table 3. The CCII− shown at the bottom of Fig. 3 was designed with the same bias current and the same design considerations.

Using these stages, one can build an OFA by connecting the output of the single-output OTA to the Y-input of the CCII−, and one can build the CFB OTA by connecting the Z-output of the CCII− to one input of the balanced-output OTA. We did this, and used both amplifiers to build V–I converters with a transconductance of 520 µS. In order to make the speed of the two circuits identical, the OFA needed a $C_C = 9$ pF, while the CFB OTA needed a C_C of only 2.5 pF.

The simulated AC transfer functions (simulated using BSIM 3v3 models) are shown in Fig. 4. It can be seen that the CFB-OTA circuit has the smaller phase lag, which may play a role in some applications. This is so because the outputs of the CFB OTA are symmetrical, and the phase lag is compensated by feedback, whereas the large phase lag in the OFA circuit is there because

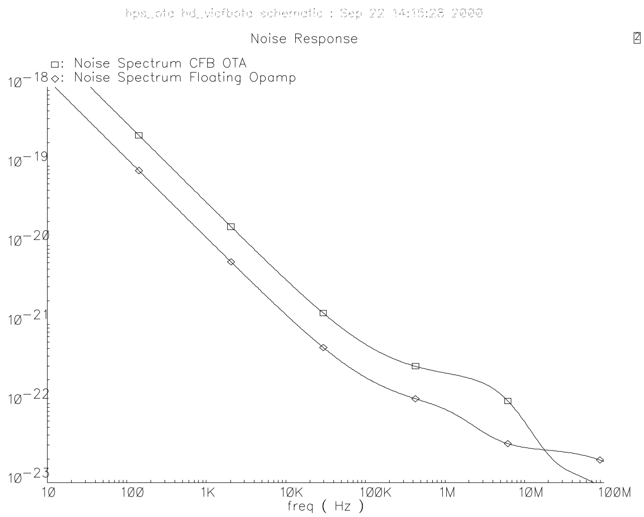

Figure 5: Noise spectra of both circuits.

the current mirrors M 61–M 93 are outside the feedback loop. Of course, phase lag compensation by feedback has implications on the maximum speed of the circuit. The C_{C} of the CFB OTA circuit cannot be made much smaller without compromising the stability of the circuit, whereas the OFA circuit could still be made much faster by decreasing the value of C_{C}.

Transient simulations with both circuits show that the THD for a 100-kHz signal reaches 1 % for an input signal magnitude of 7.8 mV in the CFB-OTA circuit and only 2.5 mV in the OFA circuit, which is a factor of 10 dB lower. This confirms the theoretical argument given above for the better linearity of the CFB OTA circuit. Looking at noise, one finds, as expected, that the CFB OTA circuit is noisier than the OFA circuit. The factor between the two noise spectra shown in Fig. 5 is 8 dB, thus if one looks at the SNR at 1 % THD, the CFB-OTA circuit is only 2 dB better than the OFA circuit.

It follows from this discussion that if linearity is most important, the CFB-OTA circuit should be used, while the OFA is more suitable for low-noise applications and also makes it possible to build faster V–I converters. Note also that the two amplifiers could both be made faster in another way, namely by using a CCII+ instead of a CCII−. This can be done by omitting the transistors M 71–M 83. If this is done with a CFB OTA, the resulting circuit will still be a CFB OTA, but if it is done with an OFA, the resulting circuit is not an OFA anymore, at least not in the strict sense, because it does not meet (2) anymore. Thus the modified CFB OTA will still work in all applications, but the modified OFA will only work in those applications where the sign of i_3 in the equation $i_4 = -i_3$ is not relevant.

We decided to use the more complicated but slower circuits to give a comparison that is as fair and as expressive as possible. For the same reason, the common-mode feedback circuitry and the offset-compensation circuitry needed in a real application were omitted, since they would be quite different for the CFB OTA and the OFA. It can, however, be expected that adding these circuits to both amplifiers will not qualitatively change the discussion in this section.

5. CONCLUSION

In this paper, a new kind of operational amplifier is discussed, the current-feedback OTA. Theoretical discussions and simulations of an application example show that the CFB OTA can have advantages over the operational floating amplifier (OFA), to which it is dual. Specifically, a V–I converter built with a CFB OTA is much more linear than the same circuit built with an OFA. Since the CFB OTA is essentially the same as a current opamp, additional circuitry for common-mode rejection and offset compensation can be built as for conventional current opamps. Although it is not in any general way better than any of the other operational amplifiers, the CFB OTA may have advantages in specific applications. Its introduction slightly broadens the horizon of analogue IC design, and almost for free, because most current opamps found in the literature can be used as CFB OTAs without adding or re-sizing a single transistor.

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