ota

The OTA (Operational Transconductance Amplifier) is a new type of operational amplifier which was introduced by RCA a few years ago. The most important difference from a normal operational amplifier is that an OTA does not work as a voltage amplifier but as a voltage-driven current source. The gain can be determined externally by the value of the output load resistor, and by the so-called bias current. The latter makes it possible to control the gain instantaneously over a range of about 80 dB by an external potential. Since the OTA will be used in several Elektor projects, an explanation of the working principles of this device should prove useful.

As the gain in an OTA can be controlled by the current from an external source (the bias current I_{ABC}), possibilities are opened up for new applications which have up to now been difficult to perform satisfactorily with discrete components. A simple application of the OTA, for example, is amplitude modulation. Although it is basically possible to effect this with one or more discrete transistors, closer inspection shows that discrete circuits do not achieve all forms of amplitude modulation really satisfactorily. Tremolo (amplitude modulation of a signal which is to be reproduced acoustically) is not easy to achieve electronically without relatively high distortion or interference. Other applications of the OTA such as multiplexing or sampling of signals are more successful than with other methods because of the OTA's high slew rate of 50 V/μsec.
Automatic volume control is also an obviously attractive application for OTAs. More applications of two types of OTA, the CA 3080 and the CA 3094 AT, will be given in future issues. These are the most interesting of the large range of OTAs which have been developed by RCA. The CA 3094 AT has in fact been developed from the CA 3080, and the only basic difference concerns the output circuit.

Linear transconductance (forward slope)

Before using the OTA in practical circuits, it is important to understand the meaning of the term 'forward slope' for which the abbreviation 'g_m' is used. The term g_m is expressed in mho ($1/\Omega$) or millimho ($\frac{1}{\Omega x 10^3}$). The amplification factor of a normal operational amplifier (known as a voltage amplifier) corresponds to the g_m of a voltage-driven current source (i.e. an OTA). The relationship between the output current and the corresponding input voltage of an OTA is:

$$\Delta I_{out} = g_m \times \Delta V_{in}.$$

The output signal of an OTA is thus a current which is proportional to its g_m. The output voltage (ΔV_{out}) appearing as a result of the output current, ΔI_{out}, in an OTA is the product of this current and the load resistor.

CA 3080

Figure 1 shows a simplified circuit of the CA 3080. T_1 and T_2 in figure 1 form a differential amplifier, which is also found in most normal operational amplifiers. W, X, Y and Z are known as current mirrors. A current mirror consists in principle of two transistors, one of which is connected as a diode. Figure 2 gives the circuit of a current mirror of this type. As the transistors T_a and T_b are supposedly identical, a current I' into T_a results in a second current I into T_b with the following relationship to I':

$$\frac{I}{I'} = \frac{\alpha'}{\alpha' + 2}$$

In this formula α' is the current amplification of transistors T_a and T_b. A current mirror can be regarded in practice as a current source in which the output current (I) is almost identical to the control current (I'), and in which the two currents I and I' can in fact be regarded as isolated from one another.
A disadvantage of the current mirror as shown in figure 2 is that it is sensitive to small differences in the current amplifications of transistors T_a and T_b, these differences resulting in the currents I' and I not being precisely equal. This effect can be greatly reduced by the inclusion of a third transistor (T_1 in figure 3).

Current mirror W in figure 1 has the circuit shown in figure 2, while current

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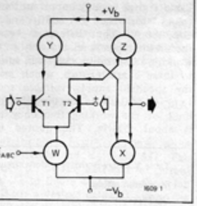

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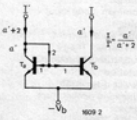

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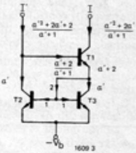

Figure 1. Simplified circuit of the CA 3080. Transistors T_1 and T_2 form the differential input amplifier. W, X, Y and Z are so-called current mirrors.

Figure 2. A current mirror can be simply made up with two transistors (T_a and T_b). The drive current I' gives rise to a current I which is proportional to I'.

Figure 3. The current mirror of figure 2 is sensitive to differences between the current gains of the two transistors (T_a and T_b). Addition of T_1 reduces this sensitivity considerably.

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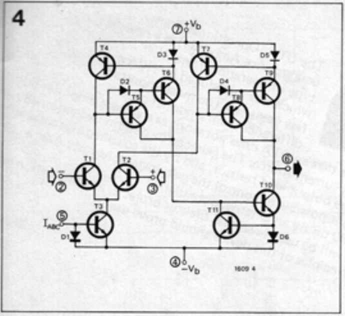

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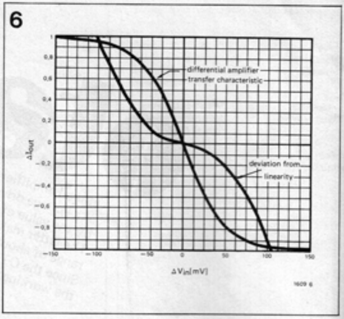

mirrors X, Y and Z are as shown in figure 3. It should also be noted that Y and Z have PNP transistors.

The complete circuit diagram of the CA 3080 is given in figure 4. The circled points indicate the connection numbers in the TO-5 housing. This housing, as seen from the upper side, is shown diagrammatically in figure 5.

In one of the RCA data sheets a drawing corresponding to figure 5 shows the reference tip between connections 1 and 8. This can lead to confusion: the drawing in figure 5 is correct.

In the circuit shown in figure 4, T_1 and T_2 are the differential input amplifier. Transistor T_3 is the common emitter impedance of this differential amplifier. The most significant difference from the input stage of a normal opamp is that T_3 is part of a current mirror, so that its collector current is equal to the bias current (I_{ABC}). The value of the collector current of T_3 determines the emitter current of the differential amplifier T_1/T_2, and this provides an effective means of controlling the overall transconductance. The g_m of an OTA in normal ambient temperatures (16°C . . . 27°C) is given by:

$$g_m = 19.2 \times I_{ABC}$$

in which g_m is expressed in millimhos ($1/\Omega \times 10^{-3}$) and I_{ABC} in mA.

In figure 4 the output signal of the OTA is taken from the collectors of T_9 and T_{10} (connection 6) which form part of the current mirrors Z and X respectively in figure 1. As I_{ABC} is varied, the g_m of the OTA changes and therefore the output current does likewise; hence:

$\Delta I_{out} = g_m \times \Delta V_{in} = 19.2 \times I_{ABC} \times V_{in}$ (at normal temperatures!)

The OTA can easily be made to operate as a voltage amplifier by connecting a load resistor R_L between the output and circuit earth. The output voltage then becomes:

$$\Delta V_{out} = R_L \times 19.2 \times I_{ABC} \times \Delta V_{in}$$

in which I_{ABC} is in mA, R_L is in kΩ, V_{out} and V_{in} are in volts.

Characteristics of the CA 3080

Table 1 gives various important limiting values for the CA 3080 and the CA 3080 A. The difference between these two types is related only to their working temperature ranges. In addition to these characteristics, which are for the specified supply voltages and an I_{ABC} of 500 µA, it can be said that the limit of the working frequency range is about 2 MHz. The quoted input

Figure 4. Complete circuit of the CA 3080 IC. The circled numbers correspond to the coding of the connecting leads.

Figure 5. Connections for the CA 3080 IC are the same as on the µA 709 except for Pins 1 and 5.
The drawing shows the top view of the IC.

Figure 6. These curves show changes in output current (ΔI_{out}) plotted as functions of changes in the input voltage (ΔV_{in}).

Figure 7. Input resistance (R_{in}) as a function of the so-called bias current (I_{ABC}).

Figure 8. As with the input resistance, the output resistance of the CA 3080 is dependent on the bias current I_{ABC}. As figure 7 and this graph show, both relationships are completely linear.

Figure 9. The CA 3080 connected as a D.C.-coupled differential amplifier. Gain can be varied by potmeter P_1 from about 30 to about 100 times.

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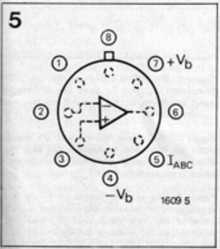

Table 1. Characteristics and maximum rating of the CA 3080 and CA 3080 A ICs.

Maximum ratings:	
DC supply voltage between $+V_b$ and $-V_b$:	36 V
Differential input voltage:	± 5 V
Common mode input voltage:	$+V_b$ to $-V_b$
Input signal current:	1 mA
Bias current (I_{ABC}):	2 mA
Output short-circuit duration:	no limitation
Device dissipation:	125 mW
Operating temperature range:	
CA 3080	0° to 70°C
CA 3080 A	−55° to +125°C

Characteristics: (V_b = +15 V; $-V_b$ = −15 V; I_{ABC} = 500 µA)	
Input capacitance:	3.6 pF
Input resistance:	26 kΩ
Input offset current:	0.2 µA
Input bias current:	2 µA
Slew rate with unity gain:	50 V/µS
Transconductance (g_m):	9600 µmho
Output resistance:	15 MΩ
Peak output current:	500 µA
Peak output voltage:	
positive	13.5 V
negative	−14.4 V
Amplifier supply current:	1 mA
Device dissipation:	30 mW

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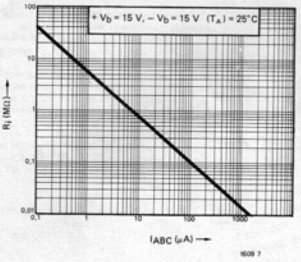

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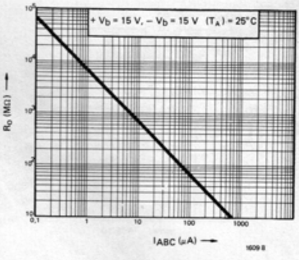

resistance of 26 k is dependent on the value of I_{ABC}.
If a value of 1 MΩ is chosen for the output load resistor, the voltage gain is easy to work out from the characteristics given in table 1:

$$A = \frac{\Delta V_{out}}{\Delta V_{in}} = R_L \times g_m$$
$$= 10^6 \times 9.6 \times 10^{-3} \approx 80 \text{ dB}$$

It can be deduced from this last formula that the voltage gain can also be varied by changing the load resistance.
The curves in figure 6 show that the overall characteristic of the CA 3080 is completely linear for small inputs to the differential amplifier. The curves show the relative values of ΔI_{out} and the deviations from linearity as functions of the relative values of ΔV_{in}. Figure 7 shows the input impedance of the CA 3080 as a function of the bias current I_{ABC}. The maximum impedance attainable in this OTA is about 40 MΩ with a bias current of 0.1 µA.

The output impedance is also, of course, dependent on the value of I_{ABC}. Figure 8 shows that this relationship is linear.

For the sake of completeness, it should be said that the characteristic of figure 7 also holds good for the CA 3094 AT. Figure 8 also holds good for the CA 3094 AT, but only for its current output. This IC has other outputs.

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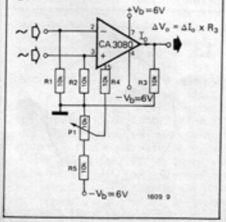

OTA - opamp

Figure 9 shows a practical circuit for the CA 3080 from which a comparison can be made with normal opamps.
The power supply is symmetrical at ± 6 V. Both inputs are D.C.-coupled and are connected to chassis earth through R_1 and R_2 respectively. Resistor R_3 of figure 9 is introduced in order to obtain voltage amplification, as in an opamp. The usual feedback from the output to the inverting input of the IC is missing, because the gain can be controlled by the bias current I_{ABC} at pin 5. I_{ABC} is easy to calculate. While recalling that the emitter of T_3 is connected to $-V_b$ (pin 4), assume that I_{ABC} is drawn via a resistor R_x from chassis earth, which is 6 V positive in relation to $-V_b$. The relationship then becomes:

$$I_{ABC} \approx \frac{V_b - 0{,}7}{R_x}.$$

In this formula, I_{ABC} is in mA, while V_b is in volts and R_x is in kΩ. The quantity 0.7 is the base-emitter potential of T_3 in figure 4. To find the value of R_x for a desired value of I_{ABC}, the formula can, of course, be rewritten:

$$R_x \approx \frac{V_b - 0.7}{I_{ABC}}.$$

In figure 9 R_x is replaced by the combination R_4, R_5 and P_1. When the slider of P_1 is at the positive end of its travel (i.e. at 0 V), the voltage across the series connection of R_x and the base-emitter junction of T_3 is V_b, so that

$$I_{ABC} = \frac{V_b - 0.7}{R_4} \approx 0.53 \text{ mA}.$$

It therefore follows that the voltage gain is:

$$A = R_3 x g_m x I_{ABC} \approx 10 x 19.2 x 0.53 \approx 100.$$

When, however, the slider of P_1 is at the negative end of its travel (the junction of R_5 and P_1), the voltage relative to $-V_b$ at the slider of P_1 is:

$$V_x \approx \frac{R_4 /\!\!/ P_1 \times (V_b + 0.7\,\frac{R_5}{R_4})}{R_4 /\!\!/ P_1 + R_5}$$
$$= \frac{5 \times 6.7}{15} \approx 2.2 \text{ V}$$

The effective voltage across R_4 is therefore:

$$2.2 \text{ V} - 0.7 \text{ V} = 1.5 \text{ V}$$

so the bias current is given by:

$$I_{ABC} \approx \frac{1.5}{10} \text{ mA} = 0.15 \text{ mA}.$$

The voltage gain is therefore:

$$A \approx R_3 x g_m x I_{ABC} \approx 10 x 19.2 x 0.15 = 29 X$$

If the gain of this IC is allowed to drop substantially, considerable distortion may result unless special attention is given to the design of the differential inputs. Should the input transistors T_1 and T_2 (figure 4) not be exactly matched, their emitter currents will differ when I_{ABC} is low, and this will cause distortion. In this connection, the following rules of thumb apply:

a. If the OTA gain is fixed, resistors R_1 and R_2 (figure 9) must have values which are lower, by a factor of at least 2 : 1, than the value of input impedance read from figure 7 for the relevant value of I_{ABC}.
b. R_1 and R_2 must have the same value when I_{ABC} is less than about 0.5 µA.
c. For fixed gain with values of I_{ABC} between 1 µA and 10 µA, the values of resistors R_1 and R_2 may differ by a factor of 2.
d. When I_{ABC} is over 10 µA, R_1 and R_2 may differ in value by a factor of 4.
e. If the gain is to be variable over a range greater than 1 : 5, resistors R_1 and R_2 must have values lower, by a factor of at least 2, than the

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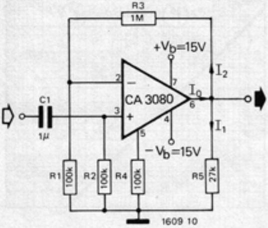

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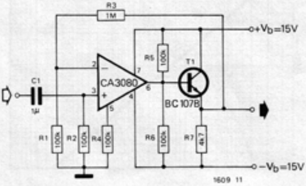

value of input impedance, indicated by figure 7, for the maximum I_{ABC}.

Negative feedback

Negative voltage feedback can be used with an OTA as it can with a normal opamp. Figure 10 gives an example of a circuit for a CA 3080. The bias current I_{ABC} is determined by R_4. The potential across this resistor is the negative power supply (15 V), less the 0.7 V base-emitter voltage which was discussed in relation to T_3 of figure 4. In this case the value of bias current is given by:

$$I_{ABC} = \frac{15 - 0.7}{10^5} = 143\ \mu A$$

so that g_m works out at

$$19.2 \times I_{ABC} = 2.74 \text{ mmho}.$$

The voltage gain given by a CA 3080 in the circuit shown in figure 10 is not determined solely by the value of the load resistor R_5, but also by R_1 and R_3. In the first place, the effective output load resistance is R_5 and $(R_3 + R_1)$ in parallel. In the second place, the voltage developed at pin 6 across this effective output load is fed back to the inverting input (pin 2) with a step-down ratio $R_1/(R_1+R_3)$.

The effective voltage gain between the input and pin 6 is thus:

$$A_f = \frac{A_o}{1 + (A_o \cdot f)} = \frac{g_m \cdot R_L}{1 + (g_m \cdot R_L \cdot f)}$$

$$= \frac{g_m \cdot [(R_1 + R_3)/\!/R_5]}{1 + g_m\,[(R_1 + R_3)/\!/R_5] \cdot \dfrac{R_1}{R_1 + R_3}}$$

$$\approx \frac{g_m \cdot R_5}{1 + g_m \cdot R_5 \cdot \dfrac{1}{11}} \approx 10x$$

(f is the feedback factor $\frac{R_1}{R_1 + R_3}$.)

It can be seen from figure 10 that if R_3 is omitted there will be no voltage fedback from the output. This is equivalent to making R_3 infinitely large in the foregoing calculations, and results in in the voltage gain being increased by a factor of about 8.

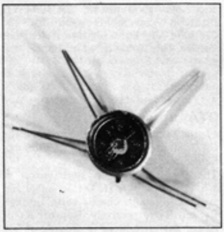

Table 2. Characteristics and maximum ratings of the CA 3094 AT.

Maximum ratings:	
DC supply voltage between $+V_b$ and $-V_b$:	36 V
Differential input voltage:	±5 V
Common mode input voltage:	$+V_b$ to $-V_b$
Input signal current:	1 mA
Bias current (I_{ABC})	2 mA
Output current:	
peak:	300 mA
average:	100 mA
Device dissipation:	
without heat sink:	630 mW
with heat sink:	1.6 W
Peak dissipation (1 mS):	10 W
Operating temperature range:	−55° to +125°C
Characteristics:	
($+V_b$ = 15 V; $-V_b$ = −15 V; I_{ABC} = 100 µA).	
Differential input capacitance:	2.6 pF
Differential input resistance: (I_{ABC} = 20 µA):	1 MΩ
Input offset current:	0.02 µA
Input bias current:	0.2 µA
Device dissipation:	10 mW
Bandwidth (Unity gain):	30 MHz
Amplifier bias voltage:	0.68 V

If a comparison is now made between the circuit of figure 10 and a normal opamp, such as the µA 741, a number of similarities become evident. Both the OTA and the opamp can be operated as voltage amplifiers, and voltage negative feedback can be used with either. Both can have either symmetrical or asymmetrical inputs, inverting or noninverting. The OTA, however, becomes a pure current source when it has no load resistance; a feature which can be advantageous for some applications. Besides this, the OTA has the feature that, as the transconductance is varied by varying the bias current, the input and output impedances also vary over

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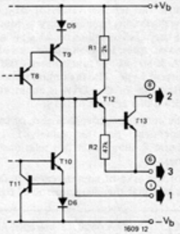

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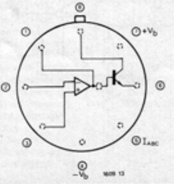

Figure 10. This circuit incorporates negative feedback from the output through R_3 to the inverting input.

Figure 11. A CA 3080 connected as an A.C.-coupled asymmetrical amplifier. Negative feedback is taken from the emitter of T_1 through R_3 to the inverting input of the IC.

Figure 12. Detailed circuit of the output section of a CA 3994 AT OTA. The difference from the CA 3080 consists of the addition of resistors R_1/R_2 and transistors T_{12}/T_{13}.

Figure 13. Functional diagram of the CA 3094 AT. The corresponding output of the CA 3080 (Pin 6) is connected in this case to Pin 1.

a wide range. If it is important for a particular application that one of these parameters (but not the other two) should have a specific value, it can be adjusted to this value by controlling the bias current.

Yet another feature possessed only by the OTA is that the gain can be controlled as may be required by D.C. or A.C. potentials, thus making amplitude modulation, sampling or switching functions possible.

Output buffer stage

Table 1 shows that the peak output current of the CA 3080 is only 500 µA, and this can be a drawback in a number of applications; moreover a 'power' OTA such as the CA 3094 AT costs twice as much.

A simple solution is given in figure 11, which shows a buffer transistor following the OTA. By this means the output current (ΔI_{out}) of the OTA is multiplied in the same ratio as the current amplification of T_1. Another advantage accruing to the addition of T_1 is that, being an emitter follower, its output impedance is low.

The load impedance which the OTA 'sees' at its output is equal to the values of R_5, R_6 and the input impedance of T_1, all in parallel.

The fact that the CA 3094 AT has been developed shows that RCA themselves have, indeed, given thought to the need for higher output currents. This OTA is equivalent to the CA 3080 except for the addition of two resistors and two transistors. Figure 12 shows in detail the output circuit of a CA 3094 AT. A comparison with figure 4 shows that R_1/R_2 and T_1/T_2 have been added in figure 12. Some of the characteristics of the CA 3094 AT are given in table 2, and the connections are given in figure 13. Pins 8 and 6 become power output points for 'sink' or 'drive' currents respectively. The low-power output, which is at Pin 6 in the CA 3080, is brought out at Pin 1 in the CA 3094 AT.