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Chapter 3

Amplifier Linearization Techniques

If the quiescent current of an amplifier stage is much larger than the maximum signal current, the current dependent small-signal parameters of the transistors will be nearly constant and independent of the signal current. Low distortion can thereby be achieved by using large quiescent currents. This will, however, in most situations result in unacceptably high power consumption. There are several methods, which can be combined, to achieve low distortion without excessive power consumption. Different linearization methods are presented in the subsections of this chapter.

The methods described are negative feedback, feed-forward, predistortion and cancellation. The descriptions are brief, concentrating on principles rather than details. The negative feedback, however, deserves more treatment, as it is very widely used and often requires advanced measures to avoid self-oscillations. Chapter 4 is therefore entirely devoted to more advanced topics regarding negative feedback.

3.1 Negative Feedback

Negative feedback was invented by H. S. Black in the 1920's [1,2]. It is based on a scheme where the error is found by subtracting the output signal, divided by the desired gain, from the input signal of the circuit. This error is fed to the input of the amplifier to be linearized, in such a way that the error at the output is counteracted, see figure 3.1.

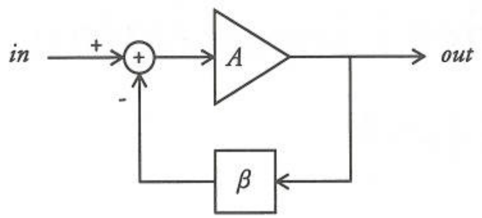

Figure 3.1: The elementary feedback model

The gain from input to output in figure 3.1 is:

$$A_{cl} = \frac{1}{\beta} \cdot \frac{\beta A}{1 + \beta A} \tag{3.1}$$

When βA, the loop gain, is large, A_{cl} is determined by just β, which is usually passive and thus more linear than A. If the gain is independent of A, the amplifier distortion due to nonlinearities in A is eliminated. The larger the loop gain, the more independent is the gain on A, and the more linearized is the amplifier. As β is fixed by the desired gain, we must make A as large as possible to maximize the loop gain. Negative feedback can be regarded as an exchange, where gain is paid for linearity.

Feedback can also be used to increase the accuracy of an amplifier, as β generally is more accurate than A. This is important, as the transistor parameters can have a large spread between different fabrications and a large variation with temperature. For integrated amplifiers particularly high accuracy can be achieved when the gain is dimension-less, as in a voltage or current amplifier. The reason is that the β network then can rely on a quotient between two passive components of the same type, which is the most accurate that can be built on an integrated circuit.

A problem with feedback is that the amplifier to be linearized is fed by an error signal, and as the amplifier needs an input signal, the error can not be completely eliminated. A solution to this problem is to use feedback boosting, which is described in section 4.4. The most important problem with feedback is the risk of self-oscillations. They can occur since the output is connected to the input, thereby forming a loop. To avoid them it is necessary to have control of the phase-shifts in the loop, that is, of A and β. This is accomplished by phase-compensation, which is treated in chapter 4. Another problem is that at high frequencies (RF) it is difficult to get enough loop gain to linearize an amplifier sufficiently.

Negative feedback is treated in several books on electronics and control theory. An early and very important book is [3].

3.2 Feed-Forward

Feed-forward was, like feedback, invented by H. S. Black in the 1920's [1,4]. The invention of feed-forward preceded that of feedback by several years. In the feed-forward scheme the error is subtracted directly from the amplifier output, instead of being fed to the amplifier input. This enables a complete cancellation of the nonlinearity, and there are no stability problems [5]. The basic feed-forward configuration is shown in figure 3.2.

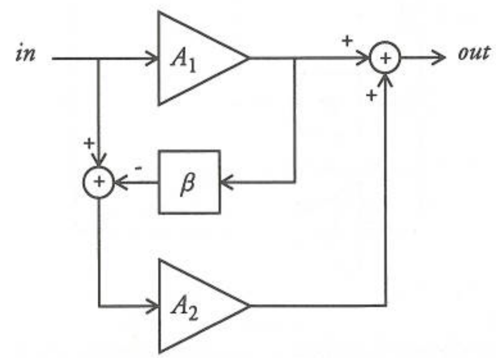

Figure 3.2: Basic feed-forward configuration

The amplifier with gain A_1 is the main amplifier to be linearized and the one with gain A_2 is an auxiliary amplifier that amplifies the error signal. The gain from the input to the output is:

$$A_{tot} = A_1 + A_2 - \beta A_1 A_2 \tag{3.2}$$

If A_2 is selected according to (3.3), the error of the main amplifier is cancelled.

$$A_2\beta = 1 \tag{3.3}$$

When (3.3) is satisfied, only the auxiliary amplifier will contribute nonlinear distortion. If this is a class A amplifier carrying small signals, the distortion levels can be very small. If A_1 is selected equal to the total gain ($1/\beta$), the input signal of the auxiliary amplifier is minimized.

Especially in high frequency applications, it might be necessary to insert time delay blocks to account for the time delays of the amplifiers, see figure 3.3. The purpose of delay τ_1 is to compensate for the delay of the main amplifier. In the same way τ_2 compensates for the delay of the auxiliary amplifier.

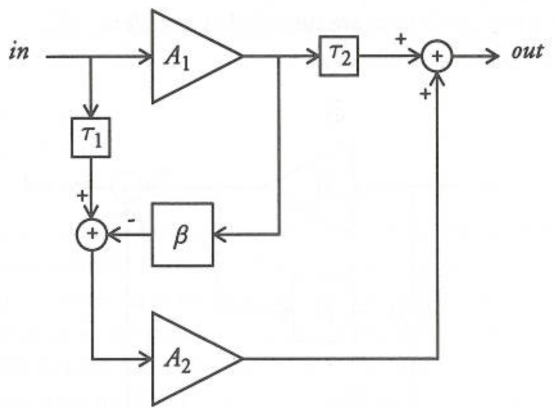

Figure 3.3: Feed-forward configuration with compensation for time-delays

One major problem, especially in integrated circuits, is how to realize the summation of signals at the output. One difficulty is that leakage from the output of the auxiliary amplifier to the output of the main amplifier will close a feedback loop, which can cause instability. Another problem is that to achieve a large linearity improvement, the accuracy of the summation must be high. The higher the

For the same reason, the gain of the auxiliary amplifier must be accurate. Feedback can be employed to achieve that. In this way the feedback and feed-forward methods can be combined.

The feed-forward principle has been used in applications with frequencies from audio [6] to RF [7]. The method is particularly attractive at RF, where feedback is not effective due to the limited amount of loop gain available at high frequencies. Instead of requiring the amplifier to be linearized to have high gain, the feed-forward technique requires the additional circuitry to be accurate.

3.3 Predistortion

If a nonlinearity is preceded by a corresponding inverse nonlinearity, the total transfer function will become linear, see figure 3.4a. This is called predistortion. If high linearity is needed over a wide bandwidth, it becomes very difficult to create the inverse nonlinearity, as the nonlinearity of amplifiers tends to be frequency dependent. The simplest example of predistortion is an MOS current mirror, figure 3.4b. Due to internal capacitances, the performance degrades as the frequency is increased [8], that is the linearized bandwidth is small, and in this case centered around DC.

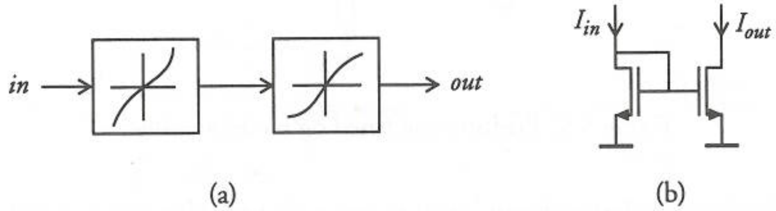

Figure 3.4: (a) The principle of predistortion (b) An MOS current-mirror is a simple example of predistortion

More advanced predistortion topologies are often used at high frequencies [9]. If the predistortion is performed at the intermediate frequency (IF), the power amplifier can be linearized at a frequency band centered around the carrier frequency. To implement the nonlinear functions needed, translinear circuits can, for instance, be used.

An advantage of predistortion compared to feed-forward is that summation at the output is avoided, and an advantage over feedback is that high loop gain is not needed. Like feed-forward, the principle is interesting for RF applications where feedback is not suitable since not enough loop gain can be achieved.

This linearization method requires nonlinear functions to be accurately realized. Furthermore, it requires the nonlinearity of the amplifier to be linearized to be accurately known. To avoid this, some sort of adaptive scheme can be used. Finding the parameter values tends, however, to be complicated, and the result is high complexity.

An alternative approach could be to use the principle sketched in figure 3.5. It uses a model amplifier to find the nonlinearity and create the pre-distorted signal. The model amplifier and its load must be identical to, or a perfectly scaled copy of, the main amplifier with load.

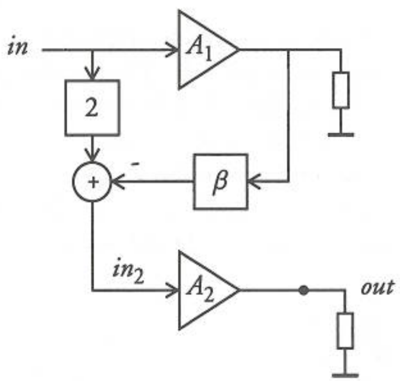

Figure 3.5: Predistortion based on model amplifier

The block (amplifier) with gain equal to two must have high accuracy and low distortion. It should also have the same time delay as A_1. Since it does not have to drive any low-impedance load, it can be implemented as a class A amplifier.

β is to be selected equal to the inverse of the small-signal gain of A_1. Assume the amplifiers to have their gain (normalized) equal to:

$$A_1 = A_2 = 1 + d \tag{3.4}$$

where d is a complex quantity representing the relative distortion. β becomes 1 in this normalized case. The input signal to the second amplifier becomes:

$$in_2 = 2 - (1 + d) = 1 - d \tag{3.5}$$

The output thus becomes:

$$out = in_2 \cdot A_2 = (1 - d) \cdot (1 + d) = 1 - d^2 \tag{3.6}$$

The distortion is thus not completely cancelled using this approach, but it can be largely reduced. If the relative distortion d for instance is 1% (-40dB), d^2 of (3.6) becomes 0.01% (-80dB). The signal to distortion ratio measured in dB is doubled by the squaring of d.

3.4 Cancellation

Cancellation is similar to predistortion. Also here one nonlinearity cancels another. The difference is that the nonlinearities cancel when they are added instead of cascaded, see figure 3.6a. A similarity to feed-forward is the addition of signals at the output.

A simple example of cancellation is an ideal square-law CMOS inverter where the N and P transistors are matched [10], figure 3.6b.

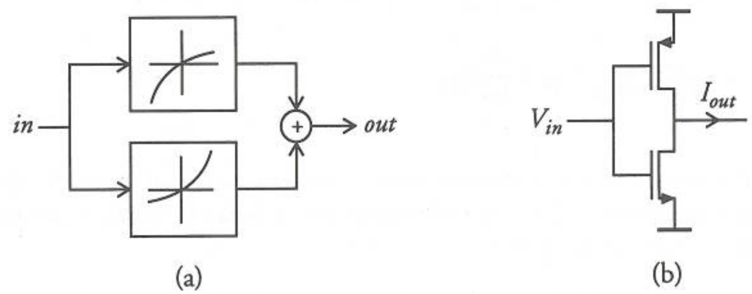

Figure 3.6: (a) The principle of cancellation (b) A CMOS inverter is a simple example of cancellation

Another example is the cancellation of even order nonlinearities in differential amplifier stages and amplifiers. In a differential topology half the input signal and the inverted half input signal are fed to ideally identical nonlinearities. At the output the signals are then subtracted. If the transfer functions of the nonlinearities are static and described by identical polynomials:

$$\begin{cases} Q_{o1} = a_0 + a_1 Q_{i1} + a_2 Q_{i1}^2 + a_3 Q_{i1}^3 + a_4 Q_{i1}^4 + a_5 Q_{i1}^5 \\ Q_{o2} = a_0 + a_1 Q_{i2} + a_2 Q_{i2}^2 + a_3 Q_{i2}^3 + a_4 Q_{i2}^4 + a_5 Q_{i2}^5 \end{cases} \quad (3.7)$$

the output becomes:

$$\begin{aligned} Q_{out} &= Q_{o1} - Q_{o2} = a_0 + a_1 \frac{Q_{in}}{2} + a_2\left(\frac{Q_{in}}{2}\right)^2 \\ &+ a_3\left(\frac{Q_{in}}{2}\right)^3 + a_4\left(\frac{Q_{in}}{2}\right)^4 + a_5\left(\frac{Q_{in}}{2}\right)^5 - \left\{a_0 + a_1\left(-\frac{Q_{in}}{2}\right)\right. \\ &\left. + a_2\left(-\frac{Q_{in}}{2}\right)^2 + a_3\left(-\frac{Q_{in}}{2}\right)^3 + a_4\left(-\frac{Q_{in}}{2}\right)^4 + a_5\left(-\frac{Q_{in}}{2}\right)^5\right\} \\ &= a_1 Q_{in} + \frac{a_3}{4} Q_{in}^3 + \frac{a_5}{16} Q_{in}^5 \end{aligned} \quad (3.8)$$

where it is readily seen that the even order terms have cancelled out each other. If the coefficient pairs of the even order terms are not exactly equal, however, the cancellation will not be perfect.

Other advantages of differential topologies are high immunity to disturbances and doubled available voltage swing. Differential topologies are also well suited for integration as the relative accuracy (matching) of devices on the same chip is excellent. A drawback is the increased complexity, and that the signals might have to be converted to differential at the input or from differential at the output.

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