FEED-FORWARD COMPENSATION SCHEME FOR FEEDBACK CIRCUITS

Inventors: Venugopal Gopinathan, Basking Ridge; Vladimir I. Prodanov, New Providence, both of NJ (US)

Assignee: Lucent Technologies, Inc., Murray Hill, NJ (US)

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Abstract:
A feed-forward compensated negative feedback circuit comprises an operational amplifier having an inverting and a non-inverting input and an output. A feedback element is connected between the output of the operational amplifier and its inverting input to form a negative feedback loop. The inverting input of the op-amp is driven with a first transconductance amplifier which produces an output current proportional to an input voltage. A feed-forward transconductance amplifier receives the input voltage and produces an inverted output current proportional to the input voltage. A feed-forward current is injected at the output of the operational amplifier. By providing at the output of the op-amp the current it would be required to carry over the feedback loop, a voltage differential at the op-amp inputs is avoided, thus eliminating parasitic current flows across the parasitic input capacitance and thereby improving the circuits overall performance. In a second embodiment of the invention, a unity-gain buffer is included in the feedback loop to produce a unidirectional path. To reduce the power requirements of the buffer, a feed-forward current is injected at a point between the feedback impedance element and the unity-gain feedback buffer such that the buffer does not need to source any current through the impedance element.
**FIG. 1A**
PRIOR ART

![Circuit Diagram A]

**FIG. 1B**
PRIOR ART

![Circuit Diagram B]
FIG. 2

\[ G_m V_{IN} \]

\[ G_m V_{IN} \]
The first term in the equation represents the transfer function for an ideal op-amp 12. The second term is a result of the non-ideal capacitive impedances.

Because of the feedback loop, the op-amp 12 must generate the same current as provided by the transconductor and the op-amp. A feedback impedance 16 is configured to bypass the Miller-compensated transductance stage and provide a current which compensates for the current directly passing through the Miller capacitor. However, the solution presented is restricted to Miller-compensated amplifiers and does not generally address the problems created by non-ideal amplifiers in negative feedback configurations with non-capacitive impedances.

An alternative solution is to introduce a unity-gain buffer 22 in the feedback loop between the output of the op-amp 12 and the impedance 16, such as shown in FIG. 1c. The purpose of the buffer 22 is to supply the feedback current $G_mV_{in}$ instead of the op-amp 22 and thereby avoid introducing a voltage differential at the input of the op-amp 12 which results in a current drain into the parasitic input capacitance. However, the buffer 22 has a finite output impedance $R_o$. Thus, the transfer function of this circuit is:

$$V_o = \frac{G_m}{V_i} (1 - YR_o)$$

(Equ. 2)

The first term in Equation 2 is the ideal behavior. The second term represents the error which results from the non-idealities of the buffer 22. In particular, the current $G_mV_{in}$ produced by buffer 22 is forced to flow through the output impedance $R_o$, 24 as well as the feedback impedance 16. Thus, there is a voltage drop in the feedback path which degrades the performance of the circuit. Although the buffer 22 could be designed to have a very small output impedance, such a buffer would require substantially more power than is generally available for high-frequency, low power devices.

Accordingly, it would be advantageous to provide a generalized op-amp feedback circuit structure with compensation for input and output capacitances. It would also be advantageous to provide an improved unity-gain buffered feedback circuit with compensation for the output resistance of the feedback buffer.

SUMMARY OF THE INVENTION

According to a first aspect of the invention, a feed-forward compensated negative feedback circuit is provided.
which comprises an operational amplifier with a conductance $g_m$ and having an inverting and a non-inverting input and an output. A non-capacitive impedance element is connected between the output of the operational amplifier and its inverting input to form a negative feedback loop. The inverting input of the op-amp is driven with a first transconductance amplifier having conductance $G_m$ and which produces an output current proportional to an input voltage. A feed-forward transconductance amplifier with a conductance substantially equal to $G_m$ receives the input voltage and produces an inverted output current proportional to the input voltage. The feed-forward current is injected at the output of the operational amplifier. By providing at the output of the op-amp the amount of current it would be required to carry over the feedback loop, a voltage differential at the op-amp inputs is avoided, thus eliminating parasitic current flows across the parasitic input capacitance and thereby improving the circuits overall performance.

In a second embodiment of the invention, the feed-forward current is injected into a unity-gain buffered feedback circuit at a point between the impedance element and the unity-gain feedback buffer. By providing the feedback current from an external source, the buffer does not need to source any current through the buffer’s output impedance since no current needs to flow through it. Preferably, in both embodiments, the transconductance amplifiers are substantially identical to each other.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The foregoing and other features of the present invention will be more readily apparent from the following detailed description and drawings of illustrative embodiments of the invention in which:

**FIG. 1a** is a schematic diagram of a conventional op-amp feedback circuit;

**FIG. 1b** is a schematic diagram illustrating the current flows in the circuit of **FIG. 1a**;

**FIG. 1c** is a schematic diagram of conventional unity-gain buffered feedback circuit;

**FIG. 2** is a schematic diagram of a feed-forward compensated negative feedback circuit according to a first embodiment of the invention; and

**FIG. 3** is a schematic diagram of a feed-forward compensated negative feedback circuit according to a second embodiment of the invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Turning to **FIG. 2**, there is shown a schematic diagram of a feed-forward compensated negative feedback circuit according to a first embodiment of the invention. The circuit includes an operational amplifier $12$ with conductance $g_m$ and having an inverting and a non-inverting input and an output. An impedance element $16$, preferably a non-capacitive impedance, is connected between the output of the operational amplifier $12$ and its inverting input. A first transconductance amplifier $14$ with conductance $G_m$ receives an input signal $V_{in}$ and has an output connected to the inverting input of the op-amp $12$, which output sources or sinks a current of $G_m V_{in}$. The parasitic input and output capacitances of the op-amp $12$, $C_{pi}$, and $C_{po}$, respectively, are also illustrated.

According to the invention, a feed-forward transconductance amplifier $30$ is provided which provides some, and preferably all of the feedback current which otherwise would have to be supplied by the op-amp $12$. As can be appreciated, the current sourced or sunk by transconductance amplifier $14$ is equivalent to the ideal feedback current. This feedback current can be duplicated by configuring the feed-forward transconductance amplifier $30$ to be substantially equivalent to transconductance amplifier $14$.

By injecting the required feedback current into the feedback loop, i.e., at the output of the op-amp $12$, the op-amp $12$ does not need to supply or sink the feedback current. Provided that the output impedance is negligible, the op-amp does not need to source or sink any current (since the feedback current is supplied externally) and thus, the op-amp $12$ is forced into a state where the input voltage differential is zero. Because the inputs of the op-amp are necessarily at the same voltage, no parasitic currents are generated across the parasitic input capacitance $C_{pi}$. As a result, the circuit behaves as an ideal circuit having a transfer function $V_{out}/V_{in} = G_m Y$, which is independent of the value of the input capacitance.

For a non-negligible output impedance, such as capacitance $C_{po}$, the circuit performance is still significantly better than without the feed-forward current. Because the feedback current is supplied by the feed-forward transconductance amplifier $30$, the only current which must be source or sink by the op-amp $12$ is that which flows through the output impedance. Mathematically, the resulting feed-forward transfer function can be written as:

$$H_{ff}(s) = \left| \frac{1}{s(1/G_m)} \right| \left| \frac{1 - \frac{C_{pi}}{G_m}}{1 + \frac{C_{po} + C_{pi}}{G_m}} \right|$$  \hspace{1cm} (Equ. 3)

If $C_{po}$ is small and $g_m$ is large, the error term approaches one, resulting in an ideal transfer function. (This result should be compared to the circuit of **FIG. 1** and Equ. 1, where the error term does not cancel).

In a preferred embodiment, the op-amp $12$ is a simple high-speed operational transconductance amplifier having a transconductance $g_m$ which is substantially larger than the $G_m$ of the input transconductance amplifiers $14$. Most preferably, $g_m$ is at least 10-times greater than $G_m$.

Turning to **FIG. 3**, there is shown a schematic diagram of a feed-forward compensated negative feedback circuit according to a second embodiment of the invention. The circuit includes an operational amplifier $12$ with transconductance $g_m$, a negative feedback impedance $16$ and a transconductance amplifier $14$ with trans-conductance $G_m$ connected to the input of the op-amp $18$ as shown. A unity gain buffer $22$ having output impedance $R_o$ is connected between the output of the op-amp $12$ and the impedance $16$. In conventional circuits, such a buffer may be introduced into the feedback loop to generate the feedback current such that the op-amp $12$ does not need to generate it. However, when current flows, there is a voltage drop across the output impedance $R_o$, degrading the performance of the circuit.

To address this problem, the output of a feed-forward transconductance amplifier $30$, having a conductance substantially equal to $G_m$, and receiving the same input signal as transconductance amplifier $14$ is connected between the unity-gain buffer $22$ and the impedance element $16$. Because the transconductance amplifiers $14$ and $30$ are substantially equal to each other and receive the same input, the current sourced or sunk by the feed-forward amplifier $30$ equals the current sunk or sourced by the input transconductance.
amplifier 14. As a result, the buffer 22 does not need to supply any current through the feedback impedance 16 and thus, there is no voltage drop across the output impedance 24 of the buffer 22.

Ignoring any output impedance associated with the op-amp, the transfer function for the circuit of FIG. 3 can be written as:

\[
\frac{V_o}{V_i} = \left( \frac{G_m}{V} \right)
\]

(Equ. 4)

In other words, the addition of the feed-forward current in the feedback path relieves the feedback buffer of the need to supply any current exceeding parasitic losses. Removing the buffer would result in a circuit similar to that in FIG. 2. However, the addition of the buffer, as supplemented by the use of the injected feed-forward current, advantageously turns the feedback path into a unidirectional path. As a result, the term in the numerator of Equ. 1 is cancelled when the feed-forward transconductance and input transconductance are equal. Adding the buffer by itself does improve the circuit but requires additional power. Using the feedforward technique described herein, where a feed forward current is injected at output of the feedback buffer, the feedback buffer does not need to supply the feedback buffer, but instead can simply serve as a unidirectional gateway. As a result, the buffer can be made smaller, thus providing an overall power advantage when compared to circuits which include the buffer but not feedforward.

As in the circuit of FIG. 2, in a preferred embodiment of the circuit of FIG. 3, the op-amp 12 is a simple high-speed operational transconductance amplifier having a transconductance \( g_m \) which is substantially larger than the \( G_m \) of the input transconductance amplifiers 14. Most preferably, \( g_m \) is at least 10-times greater than \( G_m \). While a variety of impedances can be used in the feedback impedance 16 in the circuit of FIG. 3, in a particular embodiment, the impedance 16 is a capacitor.

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While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

We claim:
1. A feed-forward compensated negative feedback circuit comprising:
   - an operational amplifier with conductance \( g_m \) and having an inverting and a non-inverting input and an output;
   - a non-capacitive impedance element connected between the output of the operational amplifier and the inverting input of the operational amplifier;
   - a first transconductance amplifier with conductance \( G_m \) and having an inverting and non-inverting input receiving an input signal and having an output connected to the inverting input of the operational amplifier; and
   - a second transconductance amplifier with conductance substantially equal to \( G_m \) and having an inverting and non-inverting input receiving said input signal and having an inverted output connected to the output of the operational amplifier.

2. The circuit of claim 1, wherein said first and second transconductance amplifiers are substantially identical.
3. The circuit of claim 1, wherein \( g_m \) is substantially greater than \( G_m \).
4. The circuit of claim 1, wherein the operational amplifier, and the first and second transconductance amplifiers are implemented in MOS.
5. A feed-forward compensated negative feedback circuit comprising:
   - an operational amplifier with conductance \( g_m \) and having an inverting and a non-inverting input and an output providing an output signal;
   - a unity-gain buffer connected to the output of the operational amplifier;
   - an impedance element connected between an output of the unity-gain buffer and the inverting input of the operational amplifier;
   - a first transconductance amplifier with conductance \( G_m \) and having an input receiving an input signal and having an output connected to the inverting input of the operational amplifier;
   - a second transconductance amplifier with conductance substantially equal to \( G_m \) and receiving said input signal, and having an inverted output connected between the unity-gain buffer and the impedance element.

6. The circuit of claim 5, wherein said first and second transconductance amplifiers are substantially identical.
7. The circuit of claim 5, wherein the impedance element comprises a capacitor.
8. The circuit of claim 5, wherein \( g_m \) is substantially greater than \( G_m \).
9. The circuit of claim 5, wherein the operational amplifier, unity gain buffer, and the first and second transconductance amplifiers are implemented in MOS.