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A Fully-Balanced Current-Tunable All-Pass Filter with CAPRIO Technique

Abstract. This paper presented the improvement of the first-order all-pass filter fully-balanced current-turnable with the Caprio technique. The proposed circuit was designed with NPN transistors, a capacitor, and a resistor. The amplitude of the signal can have been directly controlled by adding an external resistor (Ree) and has been tuneable electronically. The circuit has a relatively simple architecture. The Caprio technique can reduce total harmonic distortion (THD) to a low level. The proposed circuits were verified by the SPICE simulation, confirming the theoretical analysis.

*Streszczenie. W artykule przedstawiono udoskonalenie filtra wszechprzepustowego pierwszego rzędu, w pełni zbalansowanego z obrotnicą prądową z wykorzystaniem techniki Caprio. Proponowany układ został zaprojektowany z wykorzystaniem tranzystorów NPN, kondensatora i rezystora. Amplituda sygnału może być bezpośrednio kontrolowana przez dodanie zewnętrznego rezystora (Ree) i jest dostrajana elektronicznie. Układ ma stosunkowo prostą architekturę. Technika Caprio może zredukować całkowite zniekształcenia harmoniczne (THD) do niskiego poziomu. Zaproponowane obwody zweryfikowano symulacją SPICE, potwierdzając analizę teoretyczną. (**W pełni zrównoważony, dostrajany prądowo filtr wieloprzepustowy z techniką CAPRIO**)*

Keywords: fully-balance, Caprio technique, sensitivities, total harmonic distortion.
Słowa kluczowe: filtr wieloprzepustowy, .Caprio

Introduction

The first-order all-pass filter (APF) is called the phase shift circuit. The feature of all-pass filter is kept constant in the amplitude and shifts the phase of the signal. Nowadays, an all-pass filter is popular because the properties of an all-pass filter have been applied in electronic measurements, communications, and others [1-2]. Furthermore, the multiphase sinusoidal oscillators, high-Q band-pass filters, and other circuits have been designed by first-order all-pass filters. There are many purposes for all-pass filter design, such as temperature compensate [3-4], grounded passive [5-6], electronic controllability [7-8], and other. However, such total purposes have never been presented for reducing the high amplitude of even-order harmonics and limiting harmonic distortion. Circuits with differential inputs and balanced complementary outputs are widely used because of their good immunity from common-mode interference and the reduced generation of common-mode radiating signals [9], so the fully balanced circuit is one of them. The Caprio quad is a cross-coupled translinear technique because it has inherent base-emitter voltage (V_{BE}) cancellation and provides a very linear voltage-to-current conversion. It still provides the high linearity characteristic and reduces total harmonic distortion [10-14].

In this paper, a fully-balanced current-tunable all-pass with Caprio technique was presented by using two simple fully balanced devices. The components of the proposed circuit consist of a first-order low-pass filter, a buffer circuit, and a Caprio's quad circuit. The total harmonics have been reduced by the Caprio quad circuit. The PSpice simulation results have been confirmed by the theoretical analysis.

The proposal for a fully-balanced current-tunable All-pass filter

The fully-balanced first-order all-pass filter with Caprio's quad is shown in Fig. 1, consisting of a fully balanced first-order low-pass filter, a buffer circuit, Caprio's quad circuit, and all transistors are matched. The components of the circuit can be described as follows: The fully balanced first-order low-pass filter was modified with Caprio's technique, consisting of a different pair (Q_5, Q_6) [15-17], a Caprio's quad (Q_9 and Q_{10}), a capacitor (C_1), three resistors (R_1, R_2,

and R_{ee}), three current sink (I_f) and (I_B), and two loading diode -connected transistors (Q_7 and Q_8), where the input voltage (V_{IN}) is the base terminal of two differential pairs (Q_5 and Q_6) between points A and B, and the output voltage (V_{out}) is the collector terminal of transistors (Q_5 and Q_6) between points C and D. The buffer circuit consists of four transistors (Q_1-Q_4) and a current sink (I_f) which the input voltage (V_{IN}) is the base terminal of two differential pairs (Q_1 and Q_2) between points A and B, and the output voltage (V_{OUT}) is the emitter terminal of transistors (Q_3 and Q_4) between points E and F.
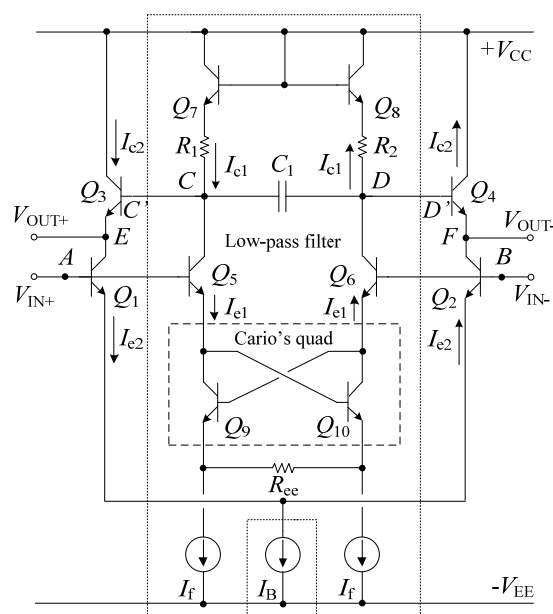
Fig.1. A fully-balanced frist-order all-pass filter with Caprio's quad

Therefore, Fig. 1 shows the first-order all-pass filter which has the input voltage between points *A* and *B* and the output voltage between points *E* and *F*.

The operation of the proposed circuit can be described as follows: The differential pairs (Q_5, Q_6) receive the input voltage at nodes *A* and *B*, which causes the emitter current (I_{e1}) of transistor Q_5 and Q_6. The I_{e1} flows from the emitter

terminal of the transistor (Q_5) to the emitter terminal transistor (Q_{10}), a resistor (R_{ee}), the emitter terminal transistor (Q_9), and the emitter terminal transistor (Q_6). The part of the current collector (I_{c1}) of the transistor Q_5 and Q_6 flows from node D to node C. Whereas the input voltage nodes A and B lead to the emitter current (I_{e2}) of transistor Q_1 and Q_2. The I_{e2} flows from the emitter terminal of the transistor (Q_1) to the transistor (Q_2). The part of the current collector (I_{c2}) of the transistor Q_1 and Q_2 flows from node F to node E.

Circuit Realization and Analysis

Referring to Figure 1, assuming that the base terminals of transistors Q_3 and Q_4 at points C' and D' are temporarily disconnected from points C and D, then the base terminals of transistors Q_3 and Q_4 temporarily connected together with an appropriate bias voltage. In such a temporary case, the resulting differential small-signal output voltage across points C and D be V_{o1}, and points E and F will be V_{o2}. The differential output current through the loading impedance (Z_1) between points C and D is caused by the differential small-signal input voltage [18]. The equation of Z_1 can be written as follows:

$$(1) \qquad Z_1 = \frac{2r_e + 2R}{1 + s\tau} = \frac{R_T}{1 + s\tau},$$

$$(2) \qquad \tau = C(2r_e + 2R) = CR_T,$$

where $R_T = (2r_e+2R)$ and r_e is the small-signal emitter resistance of the transistor ($r_e = V_T/I_f$), which r_e can be controlled by current (I_f). The V_T is the thermal voltage (26 mV at room temperature). The first-order transfer function V_{o1}/V_{in} is shown in eq. (3), representing a low-pass filter.

$$(3) \qquad \frac{V_{o1}}{V_{in}} = \frac{R_T}{1 + s\tau} \cdot \frac{1}{R_{ee}}$$

In addition, V_{in} also results in a differential output current through the loading impedance Z_2 between points E and F, where

$$(4) \qquad Z_2 = 2r_e$$

The transfer function V_{o2}/V_{in} is shown in equation (5), which represents a buffer

$$(5) \qquad \frac{V_{o2}}{V_{in}} = 1.$$

By reconnecting the base of transistor Q_3 and Q_4 with points C and D (as shown in Figure 1), the resulting differential small-signal output voltage V_{out} taken across points E and F is obtained through superposition and therefore $V_{out} = V_{o1} - V_{o2}$. As a result, the transfer function V_{out}/V_{in} is

$$(6) \qquad \frac{V_{out}}{V_{in}} = \frac{R_T - (s\tau + 1)R_{ee}}{(s\tau + 1)R_{ee}}$$

If R_T in equation (6) is equal to 2. Therefore, equation (6) is transformed into equation (7).

$$(7) \qquad \frac{V_{out}}{V_{in}} = \frac{1 - s\tau}{1 + s\tau}$$

Equation (7) shows the transfer function of an all-pass filter. The corner frequency of such a filter has the following form:

$$(8) \qquad \omega_o = \frac{1}{CR_T}$$

$$(9) \qquad \phi(\omega) = -2\tan^{-1}(\omega CR_T)$$

From equation (9), the phase response is shifted from 0° to -180° and can be controlled via R_T.

Caprio's Redue the even order by Volterra series

The Caprio technique shows a perspective current mode, differential input topology with very low input impedance and wide bandwidth. So equation (10) is a Volterra series analysis [19], the third-order intermodulation components (IM3) of the output voltage V_{out} at frequency $f + 2\Delta f$.

$$(10) \qquad IM3_{Cap} \approx \left| \frac{A_{in}^2}{8g_m^3 R_{ee}^3 V_T^2} \frac{f}{f_T} \right|.$$

The parameters in equation (10) are as follows: A_{in} is the input amplitude, g_m is the transconductance of the transistors, R_{ee} is the emitter degeneration resistor, and the f_T is the cutoff. IIP3 can be solved from equation (10) by setting $IM3_{Cap} = 1$ as follows

$$(11) \qquad VIIP3_{Cap} \approx 2\sqrt{2V_T} \sqrt{\frac{g_m^3 R_{ee}^3 f_T}{f}}$$

where $VIIP3_{cap}$ shows the third-order input referred to as the intercept point voltage of Caprio's Quad. $VIIP3_{cap}$ can be further simplified as

$$(12) \qquad VIIP3_{Cap} \approx \sqrt{\frac{f_T I_T^3 R_{ee}^3}{fV_T}}$$

where I_T is the overall current consumption.

Simulation Results

To verify the performance and theoretical validity of the proposed circuit in Fig. 1, it has been simulated using PSpice. The NPN transistors are modeled by NR200N. The gain and phase responses of the all-pass filter are shown in Fig.2. The proposed circuit in fig. 2 was biased with ±2.5V supply voltages, $C_1 = 0.1nF$, $I_f = 20\mu A$, $I_B = 20\mu A$, $R_{ee} = 5k\Omega$, and $R_{1,2} = 4k$. The simulation results represent the phase response from 0° to -180° of the APF. The voltage gain of APF was approximately 0 dB. The pole frequency of the APF was about 141kHz.
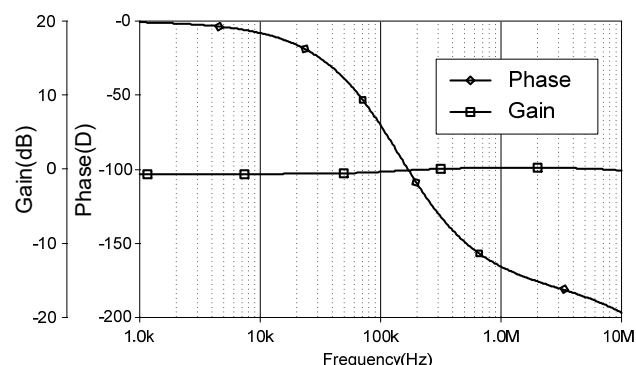

Fig.2. Gain and phase responses of proposed circuit

The phase response for different current source I_f and resistors R is shown in Fig. 3, and it can be described as follows: At a 71 kHz frequency, $I_f = 10\mu A$, $I_B = 10\mu A$, $R_{ee} = 10\Omega k$, R_1, and $R_2 = 8k\Omega$. At a 141kHz frequency, $I_f = 20\mu A$, $I_B = 20\mu A$, $R_{ee} = 5k\Omega$, R_1, and $R_2 = 4k\Omega$. At a 295 kHz

frequency, I_f = 40µA, I_B = 40µA, R_{ee} = 2.5kΩ, and R_1, and R_2 = 2kΩ. Fig. 4 shows the time-domain response of the proposed circuit when a sine wave of 30mV amplitude and 141kHz is applied as the input to the filter. The Monte Carlo (MC) method was applied to examine the tolerance error of the passive device in finding an effect on the proposed all-pass filter. The Monte-Carlo simulations were performed for 100 samples, taking 1% and 10% Gaussian deviations for the resistances and capacitors, respectively. The histogram of the gain and phase at frequency 141kHz of APF is shown in Fig. 7, Fig. 8, and Table 1. The gain of APF in Table 1 has a mean gain response of -0.24 dB, a median of -0.23 dB, and a standard deviation of 0.1. The phase of APF in Table 1 has a mean phase response of -90.64°, a median of -91.1°, and a standard deviation of 4.86.
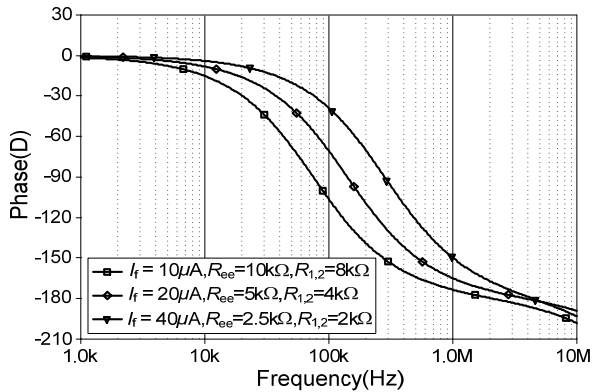

Fig. 3. Simulated phase responses of the proposed circuit when If, R1, R2, and R3 are varied.
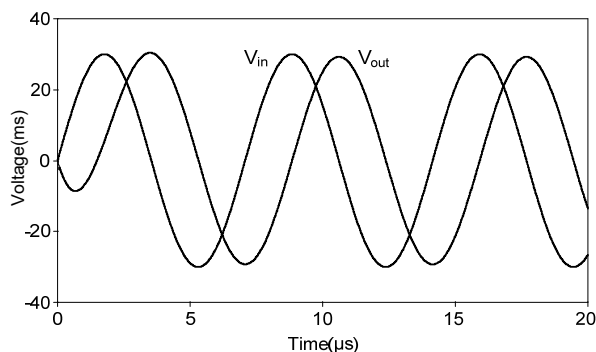

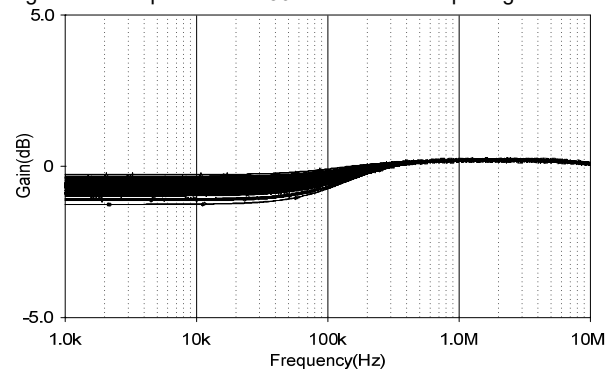Fig.4. Filter response to a 150kHz sinusoidal input signal.

Fig. 5 shows the Monte-Carlo analysis of the gain response of the all-pass filter.

Fig. 9 shows the harmonic spectrum simulation results of the conventional circuit with the proposed circuit. The results show that the conventional circuit has high harmonics at 282 kHz, 423 kHz, and 564 kHz. From fig. 9, circuits are used by the input voltage supply at 30 mV. The total harmonic distortion (THD) of the conventional circuit is 2%, but the THD of the proposed circuit is 0.09%. An

improved circuit with Caprio's quad results in reducing those high harmonics. Consequently, the total harmonic distortions (THD) are shown in Fig. 10.
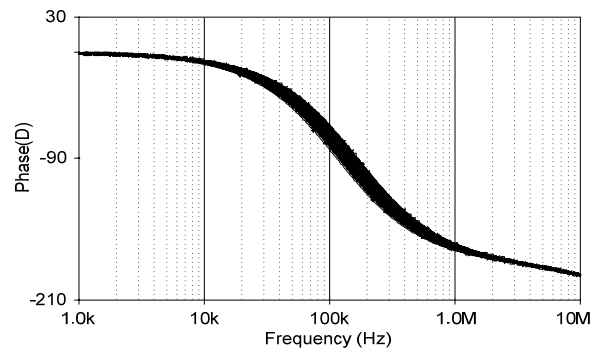

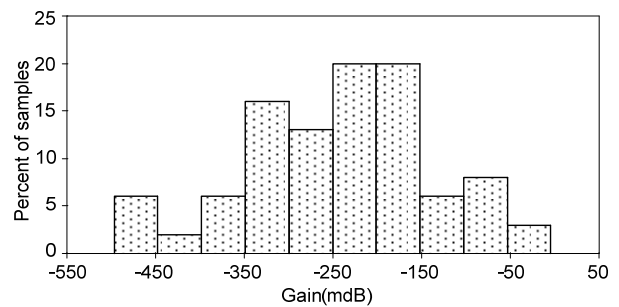Fig. 6 shows the Monte-Carlo analysis of the phase response of the all-pass filter.

Fig. 7 shows the histograms of the gain response of the proposed APF at a frequency of 150 kHz.
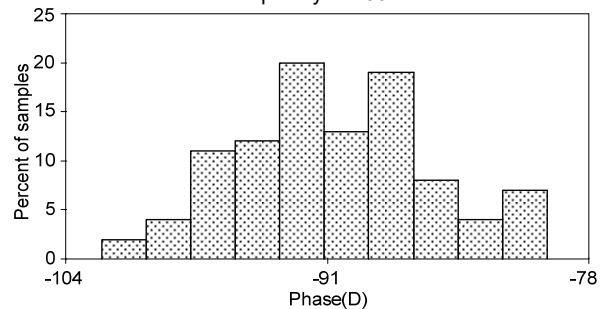

Fig. 8 shows the histograms of the phase response of the proposed APF at a frequency of 150 kHz.

Table 1. Statistical outputs of the Monte-Carlo analysis

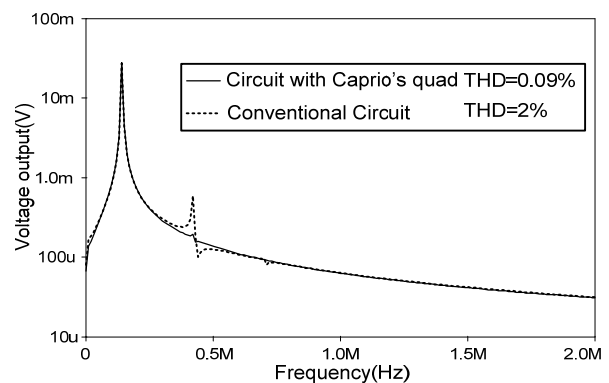| Response	Statistical components and their values			
	Number of simple	Mean	Median	Standard deviation
Gain	100	-0.24dB	-0.23dB	0.1
Phase	100	-90.64 Degree	-91.11 Degree	4.86

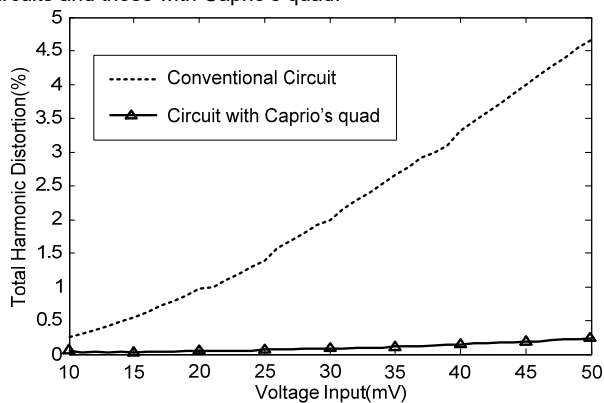Fig.9. shows the harmonic spectrum comparison of conventional circuits and those with Caprio's quad.

Fig.10. shows the percent total harmonic distortion comparison of conventional circuits and those with Caprio's quad.

Conclusion

The proposed fully-balanced current-tunable first-order all-pass filter with the Caprio technique consisted of NPN transistors, three transistors, and a capacitor. The frequency and phase response can be adjusted with the external resistors and bias current. The circuit architecture is symmetrical with different signals. The circuit has a simple. The total harmonic distortion (THD) of this design was lower than the conventional circuit. The PSPICE simulation results of the circuit agreed well with the theoretical anticipation.

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