Simulation of Transient Processes in the Fast Track-and-Hold Circuits

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Introduction

The track-and-hold circuits (THC) operate in the fast integrated analog-digital converters (ADC) as well as in the conveyer-like high precision sigma-delta modulators. The analysis in megahertz frequency range of such circuits is presented in the references [1-2].

The THC dynamic errors in the signal tracking mode for sinusoidal signal in a gigahertz frequency range were analyzed and the output signal time diagrams depending on the circuit internal and topological parasitic electrical parameters were presented in this paper. The experience gained in the earlier analysis of sample-and-hold circuits [3-5] was used in this work. The influence of the signal transfer lines with distributed parameters on the THC precision, which is an urgent problem, was evaluated in this paper [6-7].

The results of the simulation and the families of the curves allow more optimal choosing of the THC characteristics depending on the needed signal processing frequency and the THC precision.

The simulation of the track-and-hold circuit with P-Spice

The THC was simulated with P-Spice using models of the 0.5 μm integrated bipolar transistors technology. The THC was simulated in the cases when ADC precision was 8 and 10 bits, with the parasitic inductances of 0.2 nH and 0.05 nH, and the clock frequency – 5 GHz. The parasitic inductances correspond to the connection wires between THC and the outside circuits, approximately 200 μm and 50 μm in length. When designing the 8-bit THC, one least significant bit (LSB) was 6.25 mV, and when designing the 10-bit THC, 1 LSB = 1.56 mV. The analog input signal dynamic range was 1.6 V, when the supply voltage was 3.3 V.

It is convenient to estimate the THC error, represented by LSBs, in the middle point of the track mode. In the hold mode, the errors appear when the voltage of the holding capacitor is dropping. It is convenient to estimate such errors at the middle point of the hold mode. When measuring, the errors were estimated in both track and hold modes, but for simplicity, only the major error was taken into account, which allowed us to get more reliable results than those presented in [3].

The open-loop circuit with the diode bridge key was chosen for simulation and it is presented in Fig. 1.

![Simplified track-and-hold circuit](image)

**Fig. 1.** Simplified track-and-hold circuit

The simulation was performed for 4 cases – when the ADC precision was 8 and 10 bit, and in each case \( L = 0.05 \) nH and \( L = 0.2 \) nH. Two of four cases are presented in Figs. 1-2 because of the lack of place. The clock signal with the decreased amplitude and shifted on the voltage axis for better representation is presented in Figs. 1-2. The hold time constant \( \tau \) was calculated by multiplying the holding capacitance \( C_H \) by the fixed load resistance \( R_L = 1 \) MΩ. The THC errors were calculated, translated to LSB units and they are presented in Fig. 4.
Fig. 2. 8-bit THC time diagrams, when parasitic inductances $L = 0.2 \text{ nH}$. Here CLK – 5 GHz clock signal, In – analog input signal, 1 – THC output signal, when $\tau = 15 \text{ fs}$, 2 – $\tau = 30 \text{ fs}$, 3 – $\tau = 60 \text{ fs}$, 4 – $\tau = 120 \text{ fs}$, 5 – $\tau = 250 \text{ fs}$, 6 – $\tau = 0.5 \text{ ps}$, 7 – $\tau = 1 \text{ ps}$, 8 – $\tau = 2 \text{ ps}$

Fig. 3. 10-bit THC time diagrams, when parasitic inductances $L = 0.05 \text{ nH}$. Here CLK – 5 GHz clock signal, In – analog input signal, 1 – THC output signal, when $\tau = 15 \text{ fs}$, 2 – $\tau = 30 \text{ fs}$, 3 – $\tau = 60 \text{ fs}$, 4 – $\tau = 120 \text{ fs}$, 5 – $\tau = 250 \text{ fs}$, 6 – $\tau = 0.5 \text{ ps}$, 7 – $\tau = 1 \text{ ps}$, 8 – $\tau = 2 \text{ ps}$

We see in Fig. 4 that when the THC clock speed is 5 GHz, the minimal THC error is with $\tau = (120-500) \text{ fs}$. In this case, we have the THC precision of about 0.5 LSB for the 8-bit ADC and about 0.75 LSB for the 10-bit ADC. When $L$ increased from 0.05 nH to 0.2 nH, the THC precision decreased slightly. When $L = 0.2 \text{ nH}$, the transient processes in the signal hold mode (Fig. 2) lasted 45% of the whole hold time, and when $L = 0.05 \text{ nH}$ (Fig. 3), the transient processes lasted only 15% of the whole hold time. It demonstrates that it is important to choose such an ADC clock signal that comparators could measure the input signal at the correct time moment for better precision.

By decreasing the THC clock speed or the number of ADC bits, THC errors decrease even more. Another way for improving the THC precision is to choose another circuit, for example, with the closed-loop structure. New or improved circuitry decisions are constantly proposed in the
new scientific literature [1-2], which allows creating simple, precise and fast THCs.

When analyzing the THC errors, it is important to evaluate what part of the error the THC contributes to the whole ADC error, but to solve this problem more investigations need to be performed.

**Calculation of the relative dynamic error in the signal track mode**

The total relative dynamic error in the analog input signal tracking mode in the Gauss signal case can be calculated as [3]:

\[
\delta_{dG} = \sqrt{\exp\left(-2 \frac{\tau_T - \tau_R}{\tau_e}\right) \left[1 - F(U_0)\right] \times \frac{2e \Delta F_G}{\sigma^2} \times \left(2e \Delta F_G^2 + \frac{\tau_T - \tau_{RG}}{\tau_e} \left[\frac{\tau_T - \tau_{RG}}{\tau_e}\right]^2 + \left(2e \omega_s\right)^2\right)^2}.
\]

(1)

For the sinusoidal signal, expression (1) becomes simplified:

\[
\delta_d = \sqrt{\exp\left(-2 \frac{\tau_T - \tau_R}{\tau_E}\right) \times \left[1 - \frac{1}{\pi} \arcsin\left(\frac{2U_0}{U_m \omega_s \tau_H}\right) \left[\frac{2U_0^2}{U_m^2} \left(\frac{\tau_T - \tau_{RG}}{\tau_E}\right)^2 + \left(2e \omega_s\right)^2\right]^2.\right.}
\]

(2)

Here \(\tau_R\) is the amplifier recharge time constant for the sinusoidal signal, which can be calculated by equation:

\[
\tau_R = \tau_E \left[\frac{2U_m}{\pi U_0} \omega_s \tau_H - 1\right].
\]

(3)

The THC parameters can be presented as the signal / noise and distortion ratio by equation:

\[
SNR = 10 \log\left(\delta_d^{-2}\right).
\]

(4)

We see in Figs. 5-6 that when the analog input signal frequency increases, the THC precision decreases. For example, when the linear part length of the amplifiers transfer characteristic is \(U_p=0.05\) V, in order to have the analog input signal frequency of 1 GHz with 50 dB SNR, \(\tau_E = 0.2\) ps needs to be chosen, and under the same conditions when the frequency increases to 5 GHz, SNR decreases to 38 dB. The following characteristics allow us to practically choose the THC parameters for the needed frequency and precision.

**Conclusions**

The track-and-hold circuit with the clock speed of \(5 \times 10^9\) samples per second was simulated in this work. The parasitic parameters of the connection lines between the THC and external circuits were evaluated. The equations are presented in Fig. 5, when \(\tau_E = 2\) ps, \(U_p=1\) V, \(\tau_T = \tau_H = 50\) ps.

![Fig. 5. Dependences of the THC dynamic error in the tracking mode on \(f\) when \(U_p=0.01\) V (curve 1); \(U_p=0.02\) V (2); \(U_p=0.05\) V (3); \(U_p=1\) V (4); \(U_p=0.2\) V (5)](image)

![Fig. 6. Dependences of the THC dynamic error in the track mode on \(f\) when \(\tau_E = 3\) ps (curve 1); \(\tau_E = 2\) ps (2); \(\tau_E = 1\) ps (3); \(\tau_E = 0.4\) ps (4); \(\tau_E = 0.2\) ps (5); \(\tau_E = 0.1\) ps (6)](image)

The dynamic errors of the track-and-hold circuit (THC) in the signal track mode for the sinusoidal signal were analyzed. The output signal time diagrams, which depend on the parasitic electrical parameters of the internal and external circuit, were presented. The results of the modeling, when the THC is intended for the 8 and 10-bit ADC with two different sets of the parasitic electrical parameters of the THC, were presented. It has been determined that the best hold time constant is 120–500 fs for the THC clock speed of 5 GHz. In such a case, the precision of the THC is about 0.5 of the least significant bit (LSB) for the 8-bit ADC and about 0.75 LSB for the 10-bit ADC. When the values of the parasitic inductances increased from 0.05 nH to 0.2 nH, the THC precision decreased slightly. When the linear part length of the amplifier transfer characteristic is 0.05 V, in order to obtain the analog signal frequency of 1 GHz with the 50 dB SNR, the equivalent hold time constant of 200 fs needs to be chosen. The results of the research allow us to choose more optimally the THC characteristics depending on the needed signal processing frequency and the THC precision. III. 6, bibli. 7 (In English; summaries in English, Russian and Lithuanian).


Инвестируются динамические погрешности устройства слежения и хранения (УСХ) для аналогово-цифровых преобразователей (АЦП) широкополосных сигналов. Представлены временные диаграммы выходных сигналов в зависимости от схемотехнических и топологических конструктивных электрических параметров УСХ для 8 и 10 разрядных АЦП. Установлено, что при частоте квантирования 5 ГГц оптимальные пределы временной хранения сегмента сигнала составляют порядка 150–500 пс. При этом точность УСХ – 0,5 малого значащего разряда (МЗР) для 8 разрядного АЦП и 0,75 МЗР для 10 разрядного АЦП. При этой частоте, изменение конструктивной индуктивности от 0,02 до 0,2 наносекунды незначительно влияет на точность преобразования сигнала. Приведены расчетные зависимости относительной динамической погрешности УСХ от частоты входного сигнала при различных значениях линейного участка передаточной характеристики дифференциального усилителя и величины временной хранения сигнала. В результате исследования установлено, что для линейного участка передаточной характеристики дифференциального усилителя 0,05 В, временной хранения времени хранения 200 пс, максимальной частоты входного сигнала 1 ГГц, отношение сигнал/шум составляет 50 дБ. Полученные результаты исследования позволяют при разработке быстродействующих УСХ более оптимально подобрать их параметры в зависимости от частоты аналогового входного сигнала и необходимой точности АЦП. Ил. 6, библ. 7 (на английском языке; рефераты на русском, немецком и литовском яз.).