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Analytical Study of On-chip Generations of Analog Sine-wave Based on Combined Digital Signals

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Abstract—On-chip sine-wave signal generation is widely covered by literature for Built-In-Self Test (BIST) or biosensor applications. The objective is to generate pure and robust sine-wave signal with minimal hardware resources. An attractive solution consists in combining several digital signals to build this analog sine-wave. The objective of this paper is to give an analytical study of various potential solutions based on digital-based approaches. Thanks to this study, we prove that technique consisting in setting the phase shifts and various amplitude values of the square-wave signals is the most efficient approach. Moreover, this study allows the selection of the best solution in terms of parameters of the square-wave signals to cancel low-order harmonics of the generated signal.

Keywords—Harmonic cancellation, sine-wave generation, on-chip signal generation

I. INTRODUCTION

The design of integrated sine-wave signal generator is a long-term research topic. Such designs have several applications from the Built-In Self Test (BIST) [1] to impedance spectroscopy for biosensor application [2].

The main objective of designing an integrated sine-wave signal generator is to overcome the need for off-chip generation and driving the signal to the internal node. The constraints for designing such integrated generator are the size and the accuracy of the generated sine-wave signal. In order to minimize the size of the design and its sensitivity to manufacturing process variation, it is relevant to use digital resources to generate the sine-wave signal.

An initial solution, presented by figure 1 consists in generating the targeted sine-wave signal by summing square-wave signals. Unfortunately this solution can induce some glitches at square-wave signal transitions.

A more-advanced solution is presented by figure 2 [1] [2] [3] [4] [5] [6] [7]. It consists in a digital block that generates some square-wave signals with different characteristics (amplitude and/or relative phase). Then, these signals are provided to another block that operates a clever summing, aiming at cancelling some harmonics of the output signal. As square-wave signals have harmonics which amplitudes decrease by $1/k$ ($k$ is the order of the harmonic). The basic principle of harmonic cancelling is to sum some square-wave signals with different characteristics in order to sum the fundamental frequency bins and to cancel the harmonics. This process can be operated for low-order harmonic cancellation. Then, a generic low-pass filter is used to remove residual high-frequency harmonics.

In order to implement such solution, there are several parameters to set for the generation of the square-wave signals such as their amplitudes, their frequencies, their number and their relative phase-shifts. The architectures described in the literature are strongly application-driven solutions. As a consequence, there is no theoretical analysis of the optimized values of the square-wave signal parameters.

In this paper we propose an analytical study of square-wave parameters for efficient sine-wave generation. This study focuses on performances in terms of linearity of the generated sine-wave, while keeping in mind the consequences on the implementation.

In the second section, we define the parameters of the square-
wave signals that can be tuned in order to operate the harmonic
cancellation. In addition the two main solutions are given.
The third section provides the analytical study of harmonic
cancellation for the different solutions. A study of robustness
of the better solution is provided in the fourth section.

II. BASIC PRINCIPLE AND CONSTRAINTS

A. Square-wave signal adjustable parameters

In order to play with the distortion of the generated sine-
wave signal, there are several square-wave signal parameters
that can be tuned. These parameters are the amplitude,
the phase, the duty cycle and the number of square-wave signal
M. For each square-wave signal n, we define its parameters
by An its amplitude, ϕn its phase and r n its duty cycle. In
order to optimize the harmonics cancellation, for M square-
wave signals, it makes 3M parameters to study. Then we will
present some simplifications.

B. Symmetry of generated square-wave signals

As presented by figure3, using M square-wave signals to
generate the sine-wave signal, if M is an even number, M/2
signals have symmetrical phase shift compared to the other
M/2 signals. In case of odd number of square-wave signals,
m = 0 signal is in phase with the targeted sine-wave signal.
Then p = (M − 1)/2 signals have a symmetrical phase shift
compared with the other p signals. Then, we define the square-
wave signal names m going from −p to p with Am = A−m
and ϕm = −ϕ−m.
The duty cycle can be set aside. Indeed two square-wave
signals with a ϕm symmetrical phase shift are two signals
with a duty cycle of r m = π − 2ϕm. As a consequence any
duty cycle can be generated with symmetrical signals.

As described in [7], a possible solution for harmonic
cancellation is to set the ϕm phase-shifts and adjust Am
amplitudes.

C. Constraints resulting from implementation and open ques-
tions

As previously mentioned, implementation has an impact on
the accuracy and robustness of an architecture. Then, from an
integration point of view, it is easier to generate a phase shift
as a fraction of the sine-wave period rather an arbitrary phase-
shift. In addition it is easier to generate signals with identical
amplitudes rather than with arbitrary amplitudes.

As described in [7], a possible solution for harmonic
cancellation is to set the ϕm phase-shifts and adjust Am
amplitudes.

\[
\begin{aligned}
\varphi_m &= 2\pi \frac{m}{N} \\
A_m &= \cos(2\pi \frac{m}{N})
\end{aligned}
\]  

with N = 4(p + 1) and m = [−p, p]

The equation 1 presents the phase shifts ϕm that are a
fraction of the sine-wave period and the amplitudes Am that
are different for each square-wave signal m.

The equation 2 provides the Fourier series description of the
sum of the M square-wave signals.

\[
y(t) = \sum_{m=-p}^{p} \sum_{k=-\infty}^{\infty} C_{k,m} e^{ik\omega t}
\]  

The Fourier coefficients given by the equation 3 are the sum
of the Fourier coefficients of the square-wave signals.

\[
C_k(y) = \sum_{m=-p}^{p} \frac{\cos(2\pi \frac{m}{N})}{k\pi}(1 - e^{ik\pi})e^{-ikm2\frac{\pi}{N}}
\]  

The equation 4 is the development of equation 3.

\[
C_k(y) = \sum_{m=-p}^{p} \frac{e^{2\pi \frac{m}{N}} + e^{-2\pi \frac{m}{N}}}{2} e^{-ikm2\frac{\pi}{N}}
\]

\[
= \frac{2}{k\pi} \sum_{m=-p}^{p} \frac{e^{2\pi \frac{m}{N}(k-1)} + e^{-2\pi \frac{m}{N}(k+1)}}{2}, \text{ for odd } k
\]  

Considering that the sum of the roots of unity is zero. We
can observe that \(\sum_{m=-p}^{p} e^{-2\pi \frac{m}{N}(k+1)}\) cancels when k is not
equal to N − 1. This implies that \(C_k(y)\) is equal to zero except
for \(k = 1, 4(p + 1) - 1, 4(p + 1) + 1, 8(p + 1) - 1, 8(p + 1) + 1
...etc\)
Then we demonstrate that thanks to this approach harmonics below $4(p + 1) - 1$ are cancelled.

Figures 4 and 5 respectively provide the temporal and spectral representation of a sine-wave signal for $p = 2$.

\begin{equation}
C_k(y) = \sum_{m=-p}^{p} \frac{-i}{k\pi} e^{-ik\varphi_m}, \text{ for odd } k
\end{equation}

To define the values of the $\varphi_m$ phase-shifts, we propose to minimize the harmonic distortion ratio provided by equation 7.

\begin{equation}
HD_{N_{\text{har}}} = \sqrt{\sum_{m=2}^{N_{\text{har}}} |C_k|^2}
\end{equation}

For the first integer values of $N_{\text{har}}$ we run a search for a minimum on $HD_{N_{\text{har}}}$ with equation 7. We observe that it is possible to cancel $HD_{N_{\text{har}}}$ when $N_{\text{har}}$ is below $2p + 3$.

Figures 6 and 7 respectively provide the temporal and spectral representation of a sine-wave signal generated for $p=3$.

\begin{equation}
\begin{cases}
\varphi_m \text{ adjustable} \\
A_m = 1
\end{cases}
\end{equation}

Let us consider the Fourier coefficients of the generated signal:

\begin{equation}
C_k(y) = \sum_{m=-p}^{p} \frac{-i}{k\pi} e^{-ik\varphi_m}, \text{ for odd } k
\end{equation}

Regarding the two previous analytical study, we can conclude that in terms of linearity, the first approach is more
efficient because it cancels more harmonics. In addition, it seems that the requested accuracy of the phase-shift is very constraining. Let's consider the equation 8 that provides the Fourier series coefficient affected by a phase-shift error.

\[
C_k(y) = \sum_{m=-p}^{p} \frac{-i}{k\pi} e^{-i(k(m+2\pi \text{deviation})}, \text{ for } k \text{ odd } (8)
\]

Figure 8 presents the harmonic distortion ratio variation for a phase-shift deviation from $10^{-4}$ to $10^{-2}$ of a period. As presented by Figure 8, we observe by simulation that harmonic distortions affected by a phase-shift error of $10^{-3}$ of a period, have an amplitude of $-50dB$.

![Figure 8. Harmonic distortion ratio variations due to varying phase-shift error for a sine-wave signal generated using square-wave signals with various phase shifts for p=2](image)

Figure 9 presents the spectrum of the sine-wave generated with p=2. This sine-wave signal is affected by jitter and/or gain error of the amplitude of the square-wave signals. We observe that the error on the amplitude of the square-wave induces an amplitude increase of the harmonics initially cancelled. The jitter induces an increase of the noise level.

![Figure 9. Spectrum of a sine-wave signal affected by amplitude error and/or jitter on the square-wave signals for sine-wave signal generated using square-wave signals with various amplitudes for p=2](image)

IV. ROBUSTNESS STUDY

In this section, we study the impact of errors on the linearity for the generation using adjustable amplitudes of square-wave signals. The main errors are phase-shift error, jitter and gain error on amplitude.

As mentioned in section II-A one of the parameters to vary is the number of square-wave signals to generate. The optimized number of these signals is included into the parameter $M$ of the previous analysis. $M$ is linked to the $p$ parameter. As the definition of the $p$ value is linked to the number of harmonics to cancel, the number of square-wave generators to design will be linked to the specification of the targeted application.

According to the analytical study and simulation results we propose some features for an efficient implementation. Using five sine-wave signals ($p = 2$), we can cancel harmonics below the eleven order. To generate a 10MHz sine-wave signal, a 120MHz clock frequency is needed. The architecture with fixed phase shift and variable amplitudes is optimally demanding for its digital clock as it is a multiple of the generated frequency. In order to have harmonic distortions at a maximum of -50dB, jitter should be below 0.1ns and the amplitude error should be limited to 1%.

V. CONCLUSION

This work is in the field of generating sine-wave signals by summing square-wave signals in order to cancel low-order harmonics. The effectiveness of the harmonic cancellation is related to the characteristics of the square-wave signals. Two approaches are generally implemented. The first approach consists in setting the phase shifts according to the implementation...
Fig. 10. Harmonic distortion ratio of a sine-wave generated using square-wave signals with various amplitudes affected by different amount of jitter technique and setting various amplitude values of the square-wave signals. The second approach is the inverse. It consists in setting the different amplitudes at the same value and setting various phase shifts of the square-wave signals. We have analytically proven that for a given number of square-wave generators, the first approach allows to cancel a higher number of harmonics. In addition, considering targeted specifications, we have proven by simulation that the first approach is less constraining in terms of clock generation.

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