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A Multi-bit VCO-based Linear Quantizer with Frequency-to-current Feedback using a Switched-capacitor Structure

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** Short Paper*

***Abstract*:** In this letter, we present a new linearization method for a voltage controlled oscillator (VCO)-based quantizer in an analog-to-digital converter (ADC). The nonlinearity of the VCO generates unwanted harmonic spurs and reduces the signal-to-noise and distortion ratio (SNDR) of the VCO-based quantizer. This letter suggests a frequency-to-current feedback method to effectively suppress harmonic distortion. The proposed method decreases the harmonic spurs by more than 53 dB. And a VCO-based quantizer employing the proposed linearization method achieves a high SNDR of 74.1 dB.

***Keywords*:** VCO, Quantizer, Low harmonic distortion, Frequency-to-current feedback

1. Introduction

Recently, there are difficulties in voltage-domain circuit design with decreases in supply voltage with complementary metal-oxide semiconductor (CMOS) technology scaling down. But time resolution has improved to under tens of picoseconds in the 90nm CMOS process because the effect of the parasitic component is decreased [1]. Therefore, design of time-based circuits (for example, the frequency-to-digital converter (FDC) or the time-to-digital converter (TDC) using a sub-micron CMOS process, is of great interest.

The VCO-based quantizer is usually composed of a VCO and a phase counter, as shown in Fig. 1(a). A VCO generates the phase proportionally by input voltage. The output frequency is quantized by counting edges using a phase counter, such as a FDC. The quantization noise of the previous sample affects that of the current sample, because the VCO generates continuous phase output. So, a VCO-based quantizer can achieve inherent first-order quantization noise shaping [2].

The main design difficulty of a VCO-based quantizer is attributed to the nonlinearity of the VCO gain, as depicted in Fig. 1(b), which generates harmonic spurs as illustrated in Fig. 1(c), and consequently, reduces the SNDR and effective number of bits (ENOB) of a quantizer. Several techniques have been proposed to compensate for this nonlinearity. Kim et al. [2] used a digital reverse-mapping circuit of the nonlinear VCO gain using an external FPGA at the end of the quantizer. Hamilton et al. [3] and Yoon et al. [4] employed two identical VCO-based quantizers to remove odd harmonic spurs. However, even harmonics still remain. Iwata et al. [5] and Straayer and Perrott [6] employed analog feedback using a digital-to-analog converter (DAC), which needs many complex analog components.

In this paper, we present a simple and effective linearization technique for reducing harmonic distortion of a VCO-based quantizer using frequency-to-current feedback, which can be easily integrated in a small chip area and can suppress all the harmonic spurs.

2. Linearized Multi-bit VCO-based Quantizer Design

Fig. 2(a) shows a block diagram of the proposed VCO-based quantizer. The frequency-to-current feedback structure for improving the linearity of the VCO is applied. First of all, the phase counter changes the VCO output phase to a digital code at every clock edge. At the same time, the output frequency of the VCO is sampled and is converted to current in the frequency-to-current (FC) converter. The converted current is compared with input current V_{in}/R. The error current is integrated into the loop

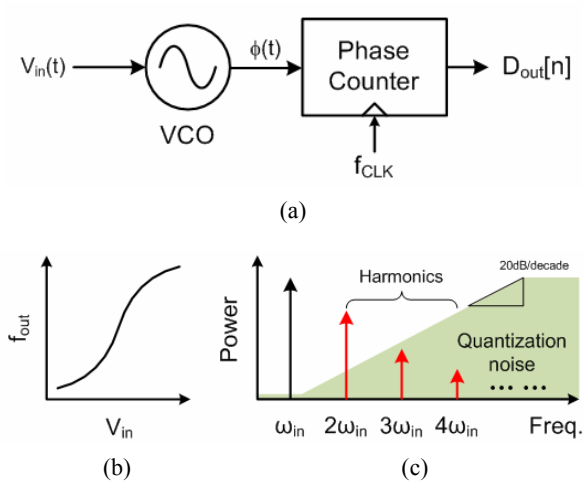

Fig. 1. A conventional VCO-based quantizer (a) Block diagram, (b) Nonlinear VCO gain, (c) Output spectrum.

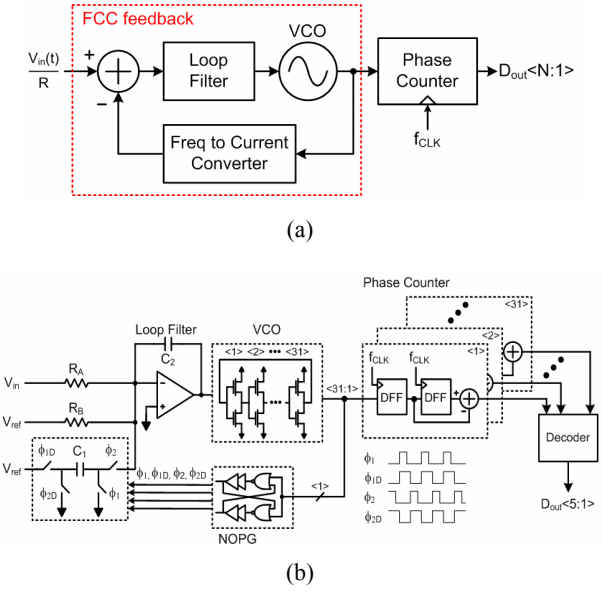

Fig. 2. The proposed VCO-based quantizer (a) Block diagram, (b) Detailed circuit.

filter. And finally, output voltage of the loop filter controls the VCO.

The detailed circuit is shown in Fig. 2(b). The VCO makes 31 phases in the proposed structure. The phase counter consists of the 31 arrays, and each one is composed of two D flip-flops and a subtractor as the XOR gate. Counting the VCO edge's previous and current clock makes the thermometer 31-bit output data from the difference of the previous and current counting data [2, 6]. Consequently, we achieve the binary five-bit output value from the thermometer 31-bit data using the thermo-to-binary decoder. The switched capacitor circuit, which is driven by one of the 31-phase VCO outputs through the non-overlapping phase generator (NOPG), is employed for frequency-to-current conversion. The switched capacitor acts as a resistor, inversely proportional to the clock frequency, with a value of $1/(C_1 \cdot f_{vco})$. The net current through the integrating capacitor C_2 should be zero in the

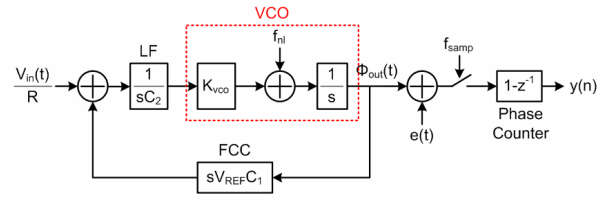

Fig. 3. The nonlinear model of the proposed VCO-based quantizer.

steady state with the FC converter current and the reference current V_{ref}/R_B. Assuming the operation amplifier is ideal, the node equation can be obtained by applying Kirchhoff's current law with the input current [7].

$$\frac{v_{in}-V_{\text{int}}}{R_A}+\frac{V_{ref}-V_{\text{int}}}{R_B}=f_{vco}\cdot C_1\left(V_{ref}-V_{\text{int}}\right) \tag{1}$$

The reference voltage V_{ref} is usually set to V_{DD}. And if all the circuits are realized differentially, V_{int} can be set to zero. Then, rearranging the above equation, the VCO output frequency becomes

$$f_{vco}=\frac{1}{R_B C_1}+\frac{v_{in}}{V_{REF}}\frac{1}{R_A C_1}=f_c+\Delta f\cdot v_{in} \tag{2}$$

where f_c is the center frequency, and Δf is the tunable frequency range. The center frequency and the tunable range can be adjusted independently by R_A, R_B, and C_1.

3. Nonlinearity Reduction

The relationship between the frequency and the control voltage of a VCO can be simplified in the phase domain, as shown in Fig. 3. The nonlinear relation between the frequency of the VCO and the control voltage can be expressed as:

$$f_{vco}=K_{vco}\cdot v_c+a_2\cdot v_c^2+\cdots=K_{vco}\cdot v_c+f_{nl} \tag{3}$$

The first term ($K_{vco} \cdot v_c$) represents the linear part; the second and third terms (f_{nl}) designate the nonlinear parts. The nonlinear part generates the harmonic spurs in the output. In the proposed architecture, these harmonic spurs originating from the VCO nonlinearity can be considerably reduced through negative feedback, and the amount of reduction can be estimated by the transfer function between φ_{vco} and φ_{nl}:

$$\left|\frac{\phi_{vco}}{\phi_{nl}}\right|=20\cdot\log\left(\frac{f_{f,harm}}{\sqrt{f_{f,harm}^2+\left(V_{ref}\cdot C_2\cdot K_{vco}/C_1\right)^2}}\right) \tag{4}$$

where $f_{f,harm}$ is the harmonic frequency of the input signal, $f_{vco}=\mathrm{d}\varphi_{vco}/\mathrm{dt}$, and $f_{nl}=\mathrm{d}\varphi_{nl}/\mathrm{dt}$. Since the transfer charac-

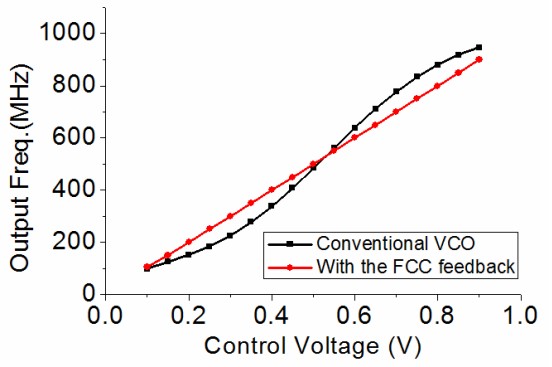

Fig. 4. Simulated output frequencies of the conventional VCO and the one with the FCC feedback vs. control voltage.

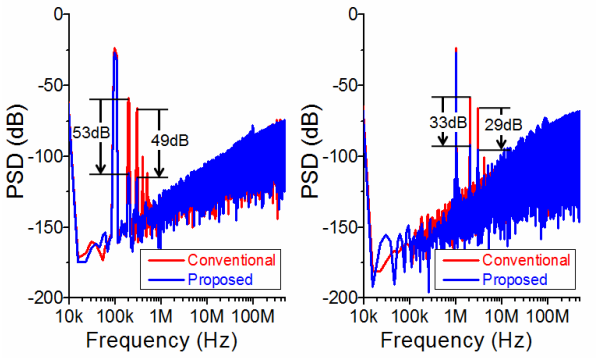

Fig. 5. Simulation result of the proposed VCO-based quantizer using Verilog-A (a) f_{in} = 100 kHz, (b) f_{in} = 1 MHz.

teristic is expressed as a high-pass filter, the lower is the applied input frequency of the quantizer, and the higher harmonic reduction is achieved.

4. Simulation Results

The proposed VCO-based quantizer is simulated using Verilog-A, where V_{ref} = 1 V, f_{clk} = 1 GHz, R_A= R_B = 20 kΩ, C_1= 100 fF, and C_2 = 500 fF. A center frequency of f_c is determined by $1/R_B \cdot C_1$ = 500 MHz with Eq. (2). A 31-phase ring-type VCO is used with a control voltage range of 0.1 – 0.9 V. Fig. 4 shows the simulated nonlinear VCO gain with a tuning range of 0.1 - 0.9 GHz and also the linearized VCO gain after the FCC feedback is applied. The frequency of the linearized VCO is measured at the output of the VCO in front of the phase count. A significant linearity improvement is achieved without changing the original gain.

The output spectrums of the proposed quantizer and conventional quantizer are shown in Fig. 5; 20 dB noise slopes are attributed to the first-order noise shaping characteristics of the phase counter using D flip-flops. As expected, high second and third harmonic spurs appear in the conventional VCO-based quantizer, as shown in Fig. 1(a). However, the harmonic spurs dwindle substantially with the proposed FCC feedback applied. Second harmonic spurs decrease by about 53 dB and 33 dB, or more, with input frequencies of 100 kHz and 1 MHz, respectively, and third harmonic spurs suppress roughly more than 49 dB and 29 dB in both frequencies, respectively. The amount of the harmonic reduction is well matched with the expected value from Eq. (4).

Table 1 presents the comparisons of the recently reported VCO-based quantizers. The proposed quantizer shows comparable or superior performance due to the novel switched capacitor linearization technique, despite the simple linearization scheme.

Table 1. Summary of the recently reported VCO-based quantizers.

Name	Configuration	f_{clk} (MHz)	BW (MHz)	SNR (dB)	SNDR (dB)
Kim et al. [2]	Digital Compensator	500	1	68.4	62
Yoon et al. [4]	Harmonic Cancellation	100	5	58.2	56.5
Straayer, and Perrott [6]	DAC Feedback	950	10	86	72
This Work	FCC Feedback	1000	5	76.52	74.1

5. Conclusion

A new linearization method for a VCO-based quantizer with low harmonic distortion is proposed. The nonlinearity of the VCO is effectively suppressed with a frequency-to-current feedback (FCC) configuration. Both even and odd harmonic spurs are simultaneously reduced in the proposed VCO-based quantizer. Second harmonic spurs decrease approximately 53 dB and 33 dB more with input frequencies of 100 kHz and 1 MHz, respectively, and third harmonic spurs decrease about 49 dB and 29 dB more in both frequencies. The proposed VCO-based quantizer achieves a high SNDR of 74.1 dB.

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