Nonlinearity Compensation Circuit for Voltage-Controlled Oscillator Operating in Linear Frequency Sweep Mode

B. K. Kang, H. J. Kwon, B. K. Mheen, H. J. Yoo, and Y. H. Kim

***Abstract*—A circuit that can compensate for nonlinearity in frequency modulation of a voltage-controlled oscillator (VCO) is proposed. The circuit uses a fixed-length delay line and an analog phase-locked loop (PLL). It sweeps the frequency of VCO output linearly in time and easily adjusts the rate of frequency sweep. For a VCO operating in a frequency range of 5.3 $\sim$ 5.4 GHz, the nonlinearity in frequency modulation was measured by observing the beat frequency $f_B(t)$ between the VCO and delayed VCO outputs. The deviations of $f_B(t)$ of $\sim$28% from its average values (2, 5, and 10 KHz) were reduced to $<$2% after compensation, indicating that the linearity in frequency modulation was improved significantly independent of the rate of frequency sweep.**

***Index Terms*—Altimeter, phase-locked loop, voltage-controlled oscillator.**

I. Introduction

A CONTINUOUS-WAVE radar system, which is frequency modulated linearly in time, is widely used for measuring the distance from radar to target. It uses a frequency difference between transmitted and reflected waves to measure the distance. A schematic diagram of a typical frequency-modulated continuous-wave (FMCW) radar system for distance or altitude measurement is shown in Fig. 1. The RF output signal $f_t(t)$ of the voltage-controlled oscillator (VCO) is frequency modulated by a ramp input signal V_{IN}, and it is radiated by the antenna, reflected from a target, and returned to the antenna. The returned signal $f_t(t - t_d)$ is down-converted in the mixer with VCO output, and the intermediate-frequency (IF) of mixer output $f_t^B(t)$ is observed. When the frequency of VCO output is swept linearly in time, the IF is proportional to time-delay of the returned signal. The distance l_d between the antenna and target is measured by observing the IF. Accuracy of measurement depends critically on the linearity of frequency sweep. When a typical VCO is frequency modulated by a linear voltage ramp input, the frequency sweep of VCO output is nonlinear, due to changes of load impedance and nonlinear active components of VCO. A linear frequency sweep can be achieved by correcting the input using a predetermined error correction table that is stored in a memory device, but it is impossible to have real time frequency compensation [1].

For real time frequency compensation, typical high-precision FMCW radar systems use two IF loops: one for real time nonlinearity compensation and the other for the main signal. The nonlinearity compensation loop consists of a frequency down-converter and a processing circuit. For digital compensation, the VCO output signal is down-converted with a highly stable local oscillator (LO) and the frequency of IF signal is counted. The deviation from average IF is used for frequency compensation [2]. This method can achieve relatively elaborate control of the VCO output frequency. However, it requires a highly stable LO and is difficult to have a coherent compensation at a high frequency. For analog compensation, the VCO output is delayed by a fixed-length delay line and down-converted with the delayed signal [3]–[5]. The down-converted IF is constant if the frequency of VCO is swept linearly in time. The deviations from a constant IF are processed with an analog circuit for frequency compensation. This method has the advantage of generating a coherent output, but adjusting the rate of frequency sweep is difficult.

When the rate of frequency sweep is fixed, the IF bandwidth of the main signal loop is determined by the range of distance measurement. Adjusting the rate of frequency sweep can reduce the IF bandwidth significantly, and that results in an improved signal-to-noise ratio (SNR) of the system. The best SNR can be achieved when the rate of frequency sweep is adjusted continuously so that the IF is kept constant, and the system operates at the narrowest IF bandwidth. In this case, the distance or altitude can be calculated from the rate of frequency sweep. However, one limitation of this method is that the nonlinearity in VCO frequency modulation widens the IF bandwidth and introduces a measurement error.

This paper proposes a circuit that can compensate for nonlinearity in VCO frequency modulation. The proposed circuit can adjust the rate of frequency sweep while the IF of the mail signal is kept constant, and uses a dc voltage input to enhance the input noise immunity. The circuit uses a low frequency phase-locked loop (PLL) for frequency compensation. The dc input generates a signal for frequency sweep. A detailed description of the circuit is given in Section II, the experimental results are given in Section III, and a conclusion is given in Section IV.

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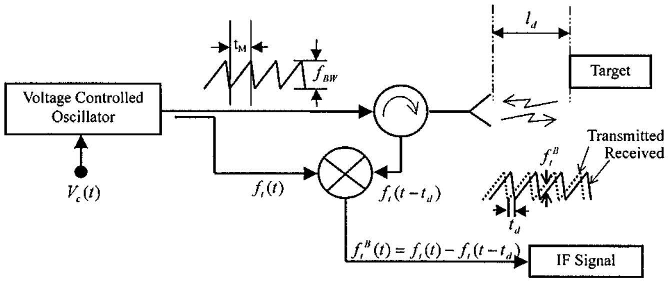

Fig. 1. Schematic diagram of an FMCW radar system for distance measurement.

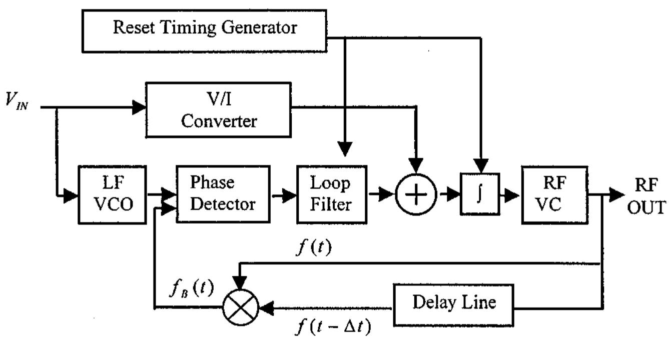

Fig. 2. Block diagram of a nonlinearity compensation circuit for VCO. The frequency of VCO output sweeps linearly in time.

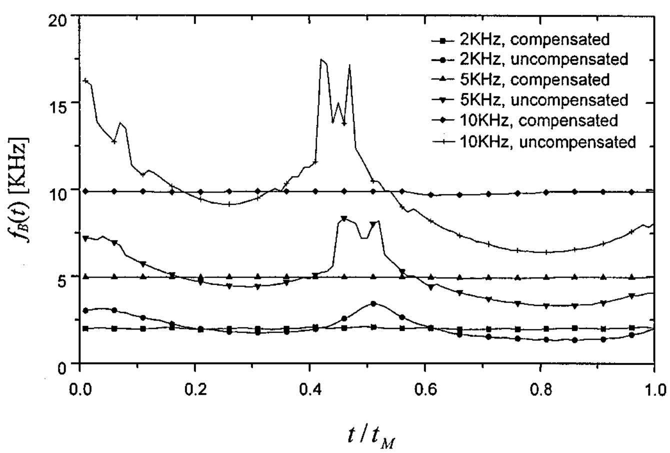

Fig. 3. Modulation properties of an RF VCO before (•, ▼, +) and after (♦, ▲, ■) nonlinearity compensation. The input dc voltage is adjusted so that $f_L = 2, 5$, and 10 KHz.

II. Nonlinearity Compensation Circuit

A VCO with a nonlinearity compensation circuit is shown in Fig. 2. It consists of an integrator, a reset-timing generator, a voltage-to-current (V/I) converter, and a PLL. The PLL circuit uses a low-frequency (LF) VCO instead of a high frequency (HF) local oscillator. A dc voltage input $V_{\rm IN}$ sets the frequency f_L of LF VCO and controls the rate of frequency sweep of RF VCO through the integrator and V/I converter. The reset-timing generator sets the modulation period t_M and determines the width of frequency sweep f_{BW}. The output of RF VCO is delayed by a fixed length delay line and it is down-converted with the RF VCO output in the mixer. The phase of down-converted

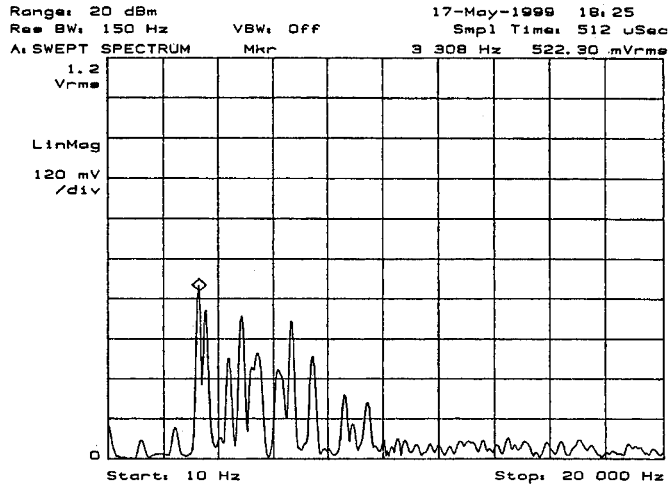

Fig. 4. Spectrum $f_B(t)$ before nonlinearity compensation for $f_L = 5$ KHz.

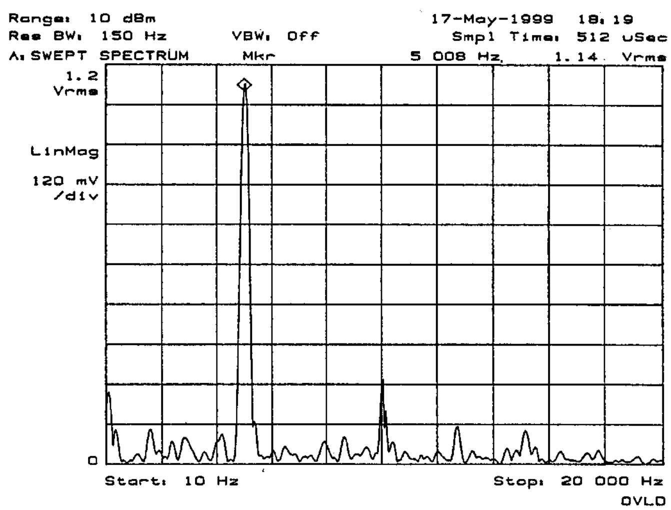

Fig. 5. Spectrum of $f_B(t)$ after nonlinearity compensation for $f_L = 5$ KHz.

IF is compared with that of LF VCO. The error signal of the phase detector is filtered by a low-pass filter, converted into a current signal, and then fed into the summing circuit where it is summed with the output of V/I converter. When the rate of frequency sweep of RF VCO is constant, the frequency of down-converted IF $f_B(t) = f(t) - f(t - \Delta t)$ is constant, where Δt is the time delay set by the delay line. In this case, the phase error is constant and the integrator generates a linear voltage ramp whose ramp rate is adjusted by the error signal. This adjusted ramp rate pushes $f_B(t)$ to follow the LF VCO frequency f_L, and the phase error becomes zero. In general, the modulation property of RF VCO is nonlinear and the rate of frequency sweep changes, resulting in a phase error. The error signal distorts the voltage ramp and makes $f_B(t)$ to follow f_L. Because of this feedback mechanism, the rate of frequency sweep of RF VCO is constant. It can be adjusted by changing f_L, i.e., by changing $V_{\rm IN}$. For a given width of frequency sweep, the modulation period is given by the following equation:

$$t_M = \Delta t \times \frac{f_{BW}}{f_L}. \tag{1}$$

III. Measurement and Results

The modulation properties of an RF VCO for three different voltage ramp inputs are measured with a delay line of $\Delta t = 1.528\ \mu$s, and the results are shown in Fig. 3. For this measurement, the frequency of VCO was swept from 5.3 to 5.4 GHz. The modulation period given in (1) was adjusted with $V_{\rm IN}$ so that $f_L = 2$, 5, and 10 KHz. For each f_L, one modulation period was divided into twenty sectors of equal duration, and the IF signal $f_B(t)$ for each sector was observed. When the phase-locked loop in Fig. 2 was disconnected (lines with marks •, ▼, and + in Fig. 3), the deviations of $f_B(t)$ from its average value are 29, 27.9, and 28.8% for $f_L = 2$, 5, and 10 KHz, respectively. These deviations in IF frequency originate from the nonlinear effect of VCO. After connecting the proposed nonlinearity compensation circuit to the system, a significant improvement on the linearity of frequency modulation is observed (lines with marks ⧫, ▲, and ■ in Fig. 3). The IF $f_B(t)$ is almost constant for each f_L, indicating that a linear frequency modulation is achieved independent of the frequency sweep rate. As discussed before, this property can be utilized for minimizing the IF bandwidth of an FMCW system for altitude or distance measurement. The deviations of $f_B(t)$ from its average values after nonlinearity compensation are 1.9, 0.4, and 0.7% for $f_L = 2, 5,$ and 10 KHz, respectively.

For $f_L = 5$ KHz, the spectrums of $f_B(t)$ before and after the nonlinearity compensation are measured, and the results are shown in Figs. 4 and 5. Before the nonlinearity compensation, the dominant peak frequency is 3.3 KHz and a spread spectrum is observed. After compensation, the center frequency shifts to 5 KHz and the spectrum is very narrow and clear.

IV. Conclusion

A nonlinearity compensation circuit for a VCO, which operates in a linear frequency-sweep mode for distance or altitude measurement, is proposed. The proposed circuit uses a fixed-length delay line and an analog PLL for nonlinearity compensation. To modulate the VCO, the circuit uses a dc voltage input, instead of a voltage ramp which is susceptible to noise and circuit nonlinearities. The circuit can adjust the rate of frequency-sweep easily without sacrificing linearity in frequency modulation. Measurement results of a VCO with the nonlinearity compensation circuit show that the linearity is significantly enhanced independently of the rate of frequency sweep. These results indicate that the proposed method offers accurate and stable VCO for an FMCW radar system for distance and altitude measurements.

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