Analysis of LO-RF Amplitude Modulation Effect in FMCW Radar

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***Abstract*—This paper investigates the effect of amplitude modulations of local oscillator (LO) and received port (RF) signal at mixer in frequency-modulated continuous-wave (FMCW) radar. The radar uses triangular chirp signals at S-band (3.0-3.4 GHz) and X-band (9.0-10.0 GHz), with 50 µs chirp duration. For short-range detection applications, 15 m target was assumed in this simulation. The power of LO and RF port in mixer in our developed FMCW radar were measured and converted into amplitude, then expressed by analytical models with terms of Fourier-expansion. For accurate expression of side lobes due to the amplitude modulation, the required number of Fourier-terms is analyzed. With the proper number of terms for each band, side lobes can be expressed sufficiently. Also, calculated results using analytical model well matches the simulation results.**

***Keywords*—Amplitude modulation (AM), Frequency-modulated continuous-wave (FMCW) radar, Fourier-expansion, beat frequency spectrum**

I. INTRODUCTION

In recent years, frequency-modulated continuous-wave (FMCW) radar has been widely used for various applications such as through-wall detection, automotive cruise control and radar altimeter [1]-[3]. One of difficulties in FMCW radar is there are unwanted side lobes which interferes to distinguish the target and clutter. Many studies have developed techniques for reducing clutter in target detection radar [4]-[5], but these were not considering the noise caused by modulated transmit signal itself. As the amplitude and the phase modulations of transmit signal make side lobes as paired-echo, result in degraded performance of target detection. One past study analyzed the effect of amplitude and phase errors in FM radar [6]. It assumed that amplitude variations of local oscillator and received signal are the same, and considered only one dominant terms of Fourier-series, but these assumptions are not suitable in real system scenario. Generally, amplitudes of LO and RF are different because the gain of other devices such as power amplifier (PA), low noise amplifier (LNA), and filter are added to received signal. In addition, it is not enough to describe amplitude modulation by one term of Fourier-series.

In our past research, dual-band FMCW radar for through-wall detection is developed [7]. In beat frequency spectrum, unknown side lobes interfere the target at some frequencies. While suffering from this problem, amplitude modulations of LO and RF port signal at mixer are considered one of the factor of these side lobes.

In this paper, the effect of LO and RF amplitude modulations in FMCW radar is investigated. For adaptation to our radar, each power of local oscillators and received signal are measured seperately, and expressed by the analytical model with Fourier-expansion. We suggested the required number of Fourier-terms to represent amplitude modulation sufficiently. For verification of this work, simulated beat frequency spectrum and calculated results using analytical model according to the number of Fourier-terms are presented.

II. LO-RF AMPLITUDE MODULATION IN FMCW RADAR

A. Analytical Model

The frequency-modulated signal that sweeps up in frequency, with time varying amplitude is given by following equation:

$$S(t) = A(t)\cos(\omega_0 t + \frac{1}{2}C_R t^2) \quad (1)$$

where ω_0 is starting radial frequency of chirp signal, C_R is chirp rate in rad/s. The time varying amplitude $A(t)$ in equation (1), can be described by Fourier-expansion about frequency band of interest and is given by

$$A(t) = A_0(1+\sum_{i=1}^{k} m_i \cos(\omega_{m_i} t)) \quad (2)$$

where ω_{m_i} represents i th modulation frequency and m_i, expressed by $m_i = A_i/A_0$ is an amplitude modulation factor at ω_{m_i}. If the signal is ideal, equation (2) reduces to A_0.

B. Adaptation to Dual Band FMCW Radar

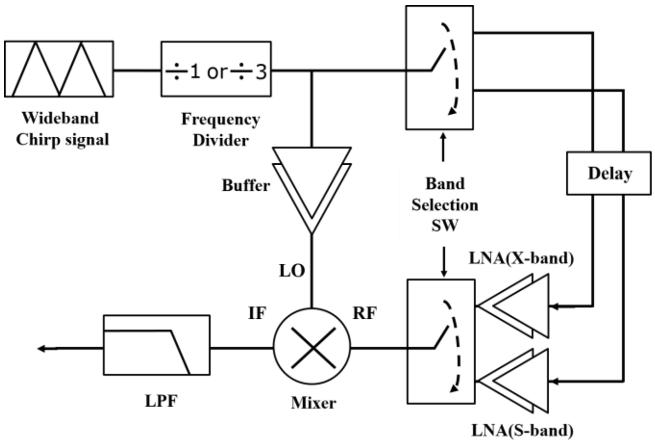

Fig. 1. Block diagram of FMCW radar

In this section, we introduces a dual-band FMCW radar system to adapt analytical model of amplitude modulation. Chirp signals of radar are generated by programmable fractional-N PLL, which makes X-band triangular shape frequency-modulated waveform. With frequency divider, X-band chirp signal is divided to S-band chirp signal and S-, X-band antennas are selected by electric switch. We assume that the target is distortionless with constant 60 dB attenuation and only time delay is considered. The block diagram of dual-band FMCW radar is shown in Fig. 1.

The power of local oscillator and received signal in the mixer are converted into peak voltage amplitude by following general equation:

$$P = \frac{V_0^{\ 2}}{2Z_0} \tag{3}$$

where P is the power and Z_0 -50 ohm is a characteristic impedance of the system. The amplitude modulation factor m_i and modulation frequency ω_{m_i} were attained by performing FFT of amplitude data. Applying equation (1) and (2), results in analytical expressions of local oscillator (LO), received signal (RF) and intermediate frequency (IF) signal given by:

$$\begin{aligned} S_{LO}(t) &= A_{LO}(t)\cos\left(\omega_0 t + \frac{1}{2}C_R t^2\right) \\ &= A_{0,LO}\left(1+\sum_{i=1}^{k} m_i \cos(\omega_{m_i} t)\right)\cos\left(\omega_0 t + \frac{1}{2}C_R t^2\right) \end{aligned} \tag{4}$$

$$\begin{aligned} S_{RF}(t) &= A_{RF}(t)\cos\left(\omega_0 (t-\tau) + \frac{1}{2}C_R (t-\tau)^2\right) \\ &= A_{0,RF}\left(1+\sum_{i=1}^{k} n_i \cos(\omega_{n_i} t)\right)\cos\left(\omega_0 \left(t-\tau\right) + \frac{1}{2}C_R \left(t-\tau\right)^2\right) \end{aligned} \tag{5}$$

$$\begin{aligned} S_{IF}(t) &= S_{LO}(t)\cdot S_{RF}(t) \\ &= A_{0,LO}\left(1+\sum_{i=1}^{k} m_i \cos(\omega_{m_i} t)\right)\cos\left(\omega_0 t + \frac{1}{2}C_R t^2\right) \\ &\quad \times A_{0,RF}\left(1+\sum_{i=1}^{k} n_i \cos(\omega_{n_i} t)\right)\cos\left(\omega_0 \left(t-\tau\right) + \frac{1}{2}C_R \left(t-\tau\right)^2\right) \end{aligned} \tag{6}$$

where m_i and n_i are amplitude modulation factor, $A_{0,LO}$ and $A_{0,RF}$ are constant amplitude without modulation of local oscillator and received signal, respectively and τ represents a time delay from target to radar. We assume that a delay of local oscillator is negligible compared to that of received signal. Because terms involving $\cos(\omega_m t)\times\cos(\omega_n t)$ are ignored provided m_i and n_i is small, equation (6) can be reduced to:

$$S_{IF}(t) = \frac{1}{2}A_0 A_1 \left[\begin{array}{l} \cos\left(C_R \tau t + \phi'\right) \\ +\sum_{i=1}^{k}\frac{1}{2}m_i\left\{\begin{array}{l}\cos\left(C_R\tau t + \omega_{m_i} t + \phi'\right) \\ +\cos\left(C_R \tau t - \omega_{m_i} t + \phi'\right)\end{array}\right\} \\ +\sum_{i=1}^{k}\frac{1}{2}n_i\left\{\begin{array}{l}\cos\left(C_R\tau t + \omega_{n_i} t + \phi' - \omega_{n_i}\tau\right) \\ +\cos\left(C_R \tau t - \omega_{n_i} t + \phi' + \omega_{n_i}\tau\right)\end{array}\right\} \end{array}\right] \tag{7}$$

where $\phi' = \omega_0 \tau - C_R \tau^2/2$. Equation (7) indicates that there appear a series of side lobes at $\pm\,\omega_m$ and $\pm\,\omega_n$ with the beat frequency ($C_R\tau$) as its center. The phase difference between the beat frequency and the third term in (7) is negligible since the value of phase difference-$\omega_{n_i}\tau$ is small at frequencies of interest which are near the beat frequency. Hence, each amplitude of sidebands is approximately ($m_i/2+n_i/2$) lower than that of the beat frequency.

III. Analysis and Verification

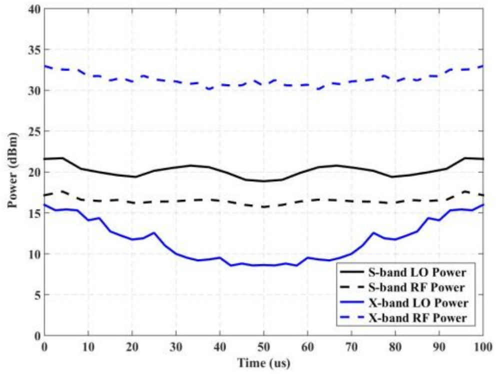

Fig. 2 Measured LO and RF power of each band. (Attenuation from target is ignored)

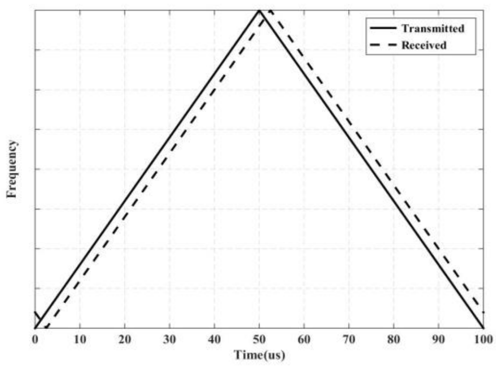

Fig. 3. Simulated triangular chirp waveform in one period.

The simulated beat frequency spectrum and calculated results using analytical model were presented. Equation (4) to (6) are based on up-chirp signal, but down-chirp signal should be involved in given system. We treat one period triangular chirp signal which sweeps up and down. Analytical model of one period chirp was easily attained by simple mathematical manipulation. Fig. 2 and Fig. 3 show triangular chirp waveform in one period and measured amplitudes of LO and RF, respectively. For applications of short-range target detection, 15 m target is assumed of which corresponding beat frequencies are 800 kHz for S-band and 2 MHz for X-band. Fig. 4 shows simulated beat frequency spectrum and calculated results using analytical model in 100% fractional band width (FBW). With one term of Fourier-expansion, side lobes due to amplitude modulation are not described completely unless most of the energy in FFT is concentrated on few terms. Therefore, to attain accurate results in the frequency band of interest, the required number of Fourier-terms, N, should be determined by following relation:

$$N = \frac{(f_H - f_L)/2}{\Omega} \tag{8}$$

where f_H is the highest frequency and f_L is the lowest frequency in bandwidth and Ω represents the frequency interval of Fourier-terms which is decided by sampling rate.

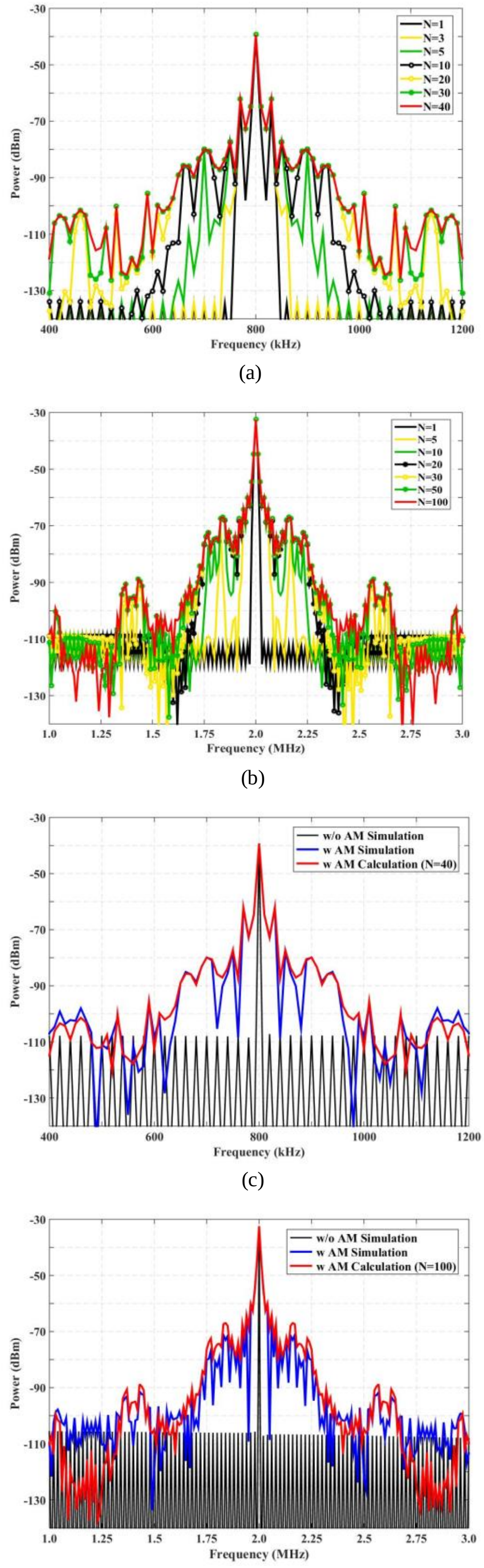

Fig. 4. Beat frequency spectrum-15 m target: Calculated results for the S-band (a) and X-band (b) chirp according to the number of Fourier-terms, N. S-band (c) and X-band (d) chirp compared with the simulation.

TABLE I. DETAILS FOR THE SIMULATION OF BEAT FREQUENCY SPECTRUM

Parameter	Value	Units
Waveform	Triangle	-
Frequency	S(3–3.4) X(9-10.0)	GHz
Chirp Rate	S(8,000), X(20,000)	GHz/s
Time Span	100	μs
Resolution Bandwidth	10	kHz
Analog to Digital Sampling Frequency	S(30), X(120)	GHz
Target distance	15	m
Beat frequency	S(0.8), X(2)	MHz
Amplitude variation	S(LO-0.43, RF-0.19) X(LO-1.44, RF-0.36)	dB
Modulation frequency interval	10	kHz
First side lobe level	S(-22.9), X(-28.5)	dBc
Calculation error of First side lobe level, when N=40(S), 100(X)	S(0.03) X(0.84)	dB
FFT length	S(3,000,000) X(12,000,000)	Points
FFT frequency bin	10	kHz

For 15 m target, the required number of Fourier-terms is 40 for S-band and 100 for X-band as shown in Fig. 4(a) and (b). In this case, calculated results well matches the simulation (Fig. 4(a) – (b)). Detail values of parameters used in simulation are presented in Table. I.

IV. CONCLUSION

Analytical model of LO-RF amplitude modulation has been adapted to dual-band FMCW radar, and the proper number of Fourier-terms to describe the side lobes due to the amplitude modulation is suggested with beat frequency spectrum. For adaptation to our radar, each power of LO and RF are measured separately and converted into amplitude. From Fourier-expansion of amplitude data, terms of modulation frequency have been attained, which correspond to position of sidebands. Beat frequency spectrum shows that the calculation with insufficient number of terms cannot express side lobes completely. To solve this problem, required number of Fourier-terms to describe the effect of amplitude modulation is suggested. Calculated results using analytical model well match the simulation, which implies that the effect of LO-RF amplitude modulations in FMCW radar could be expressed accurately only if the enough number of Fourier-terms are used.

Acknowledgment

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