A new transmitted-reference FMCW-UWB radar for gasoline tank level gauge

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Abstract - *This paper proposes a new transmitted-reference (TR) FMCW-UWB radar for use as a gasoline tank level gauge. We analyze coherent receivers with emphasis on unwanted frequencies such as Doppler frequencies. The proposed TR-FMCW-UWB radar is composed of an FFT block, a delay block, a multiplier, and an integrator block. The system model is verified through analysis and simulation. Degradation of detection performance occurs in the coherent receiver, in contrast to the proposed radar. The proposed receiver requires about 1dB more SNR than the ideal coherent receiver at the PD of 0.5. However, the performance of the coherent receiver has an effect on unwanted frequency. For PD of 0.5, the coherent receiver requires a higher SNR than does the proposed receiver when the unwanted frequency is 140 Hz.*

Keywords: Transmitted-reference, UWB radar, level-gauge, unwanted frequency.

1 Introduction

FMCW-UWB radar has recently received much attention as a level measurement sensor for gasoline tanks [1-2]. As a non-contact sensor, radar is not affected by changes in process temperature, pressure, or the gas within the vessel. In addition, the measurement accuracy is not affected by variation in density, conductivity, or dielectric constant of the measured object or by air motion above the object. These benefits play essential roles in the measurement industry due to the emergence of low-cost high-performance radar. This breakthrough has produced an unprecedented boom in the use of non-contact microwave radar transmitters for liquid and solid process level applications [3].

Microwave radar level gauge systems mostly use FMCW-UWB radar. Because FMCW-UWB radar uses wideband bandwidth, it has the advantage of detecting high-resolution distance within centimeters. However, when a liquid tank in an oil tanker is moved by waves or when the administrator puts gasoline into the tank, FMCW-UWB radar experiences a degradation of detection performance that is markedly affected by unwanted signals such as Doppler frequencies3. Through the use of a stretch processor, the transmitted signal of the FMCW-UWB radar is converted to a sinusoidal signal. FMCW-UWB radar obtains the relative distance between the radar and the object through the converted sinusoidal signal. Due to unwanted signals, FMCW-UWB radar cannot detect the relative distance exactly. Therefore, we propose a transmitted-reference (TR) FMCW-UWB radar, which is unaffected by unwanted frequencies.

This paper analyzes detection performance of coherent receiver with effects of unwanted frequency and TR-FMCW-UWB radar for use in automotive radar. Section 2 shows the system model. Section 3 shows the proposed TR-FMCW-UWB radar system. Section 4 presents the simulation results for the proposed radar. Finally, conclusions are presented in section 5.

2 System models

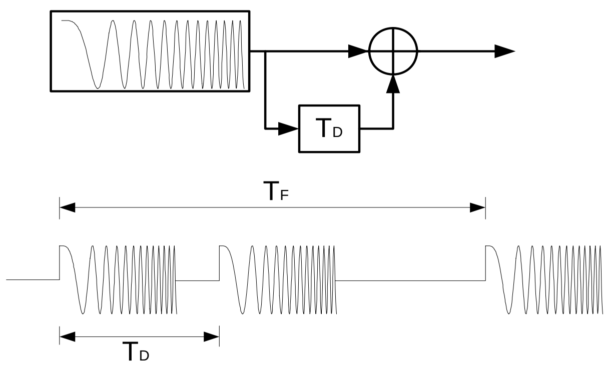

Figure 1. Signal scheme of TR-FMCW-UWB radar

This section presents the transmitted signal of the TR-FMCW-UWB radar. We assume that the TR-FMCW-UWB transmitted signal *s(t)* consists of N_P frames that can be defined as follows:

$$s(t) = \sum_{i=0}^{N_p} \cos(2\pi(f_0(t - iT_F) + \frac{B}{2T}(t - iT_F)^2)) + \cos(2\pi(f_0(t - iT_F - T_D) + \frac{B}{2T}(t - iT_F - T_D)^2)), \quad 0 \le t \le N_p T_F \tag{1}$$

where T_F is the frame duration, T_D is the interval between the reference chirp and the transmitted chirp, B is the bandwidth, and T is the signal width. Fig. 1 shows a signaling scheme generated in the TR-FMCW-UWB of Eq. (1).

The received sinusoidal signal of the TR-FMCW-UWB radar i^{th} frame through the stretch processor [4], expressed in Eq. (2), can be defined as follows:

$$r_i(t) = \cos\left(\frac{4\pi BR}{cT} t + f_0 \frac{4\pi R}{c}\right) + \cos\left(\frac{4\pi BR}{cT}(t - T_D) + f_0 \frac{4\pi R}{c}\right) + n(t), \quad 0 \le t \le T_F \quad (2).$$

Here, R is the distance between the radar and an object, c is the speed of light, and $n(t)$ is zero-mean AWGN (additive white Gaussian noise) with PSD (power spectral density) *N0/2*.

In the receiver, the received signal, as depicted in Eq. (2), passes through the mixer and the low-pass filter (LPF). The LPF output changes into a sinusoidal signal according to Eq. (2). Through an FFT processor, the frequency of the sinusoidal signal represents the relative distance between the radar and the object.

In Eq. (3), the received sinusoidal signal applied to unwanted frequency of TR-FMCW-UWB radar in i^{th} frame, can be defined as follows:

$$r_i(t) = \cos\left\{\left(\frac{4\pi BR}{cT} + f_U\right)t + f_0 \frac{4\pi R}{c}\right\} + \cos\left\{\left(\frac{4\pi BR}{cT} + f_U\right)(t - T_D) + f_0 \frac{4\pi R}{c}\right\} + n(t), \quad 0 \le t \le T_F \quad (3)$$

Here, f_U is the unwanted frequency due to moving objects. FMCW-UWB radar cannot exactly detect the relative distance between the radar and the object because the frequency of the received signal is changed by the unwanted frequency.

Our goal in this paper is to provide a detection probability of the TR-FMCW-UWB receiver that is not affected by unwanted frequency compared to the coherent receiver.

3 The proposed TR-FMCW-UWB radar

3.1 The TR-FMCW-UWB radar receiver

This section presents the proposed TR-FMCW-UWB radar receiver. Instead of a correlator using a chirp generator and exact timing control block, we use an FFT block, a delay block, a multiplier, and an integrator block in the proposed receiver.

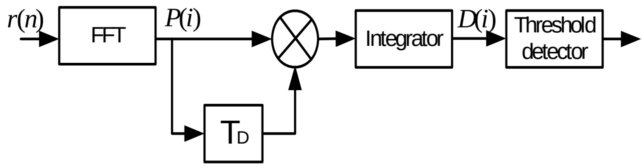

Figure 2. Block diagram of TR-FMCW-UWB radar receiver

The received signal $r(n)$ sampled values at every T_S are used as the input of the FFT processor. Passing the FFT processor, $P(i)$ can be expressed as follows

$$P(i) = \sum_{n=0}^{N-1} r(n) e^{-j2\pi in/N} \quad (4)$$

where $i = -N/2, \ldots 0, \ldots, N/2 - 1$. The value $D(i)$, as the output of TR-FMCW-UWB receiver, can be written as

$$D(i) = \sum_{i=0}^{L} P(i) P(i - T_D) \quad (5)$$

where L is the integration number. If the above result is greater than the defined threshold, we can determine that a target is present.

3.2 Performance analysis of the TR-FMCW-UWB radar

This section analyzes the performance of the TR-FMCW-UWB radar in comparison to that of the coherent receiver. If the receiver is assumed to be perfectly received without unwanted frequency, the detection probability of the coherent receiver can be given by Eq. (6) (7) [5].

$$P_D = Q(Q(P_{FA}) - \sqrt{N \cdot SNR}) \quad (6)$$

$$Q = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} t^2\right) dt \quad (7)$$

where the N-point FFT processor becomes the same function with a coherent integration of N times.

We evaluate the detection probability of the proposed TR-FMCW-UWB radar receiver. We assume that the received signal passing through the delay block and the multiplier have same distribution characteristics as those of the square of the Gaussian random variable. If $D(i)$ represents noise alone, then the probability density functions of $D(i)$ can be calculated at the receiver output as

$$p_0(D) = \frac{1}{\sigma^n 2^{n/2} \Gamma\left(\frac{1}{2} n\right)} D^{(n/2)-1} e^{-D/2\sigma^2} \quad (8)$$

where the n degree central chi-square distribution with zero mean and variance σ^2 and $\Gamma(n)$ is the gamma function. And, if a received signal is found to exist, then the probability density functions of *D(i)* can be calculated at the receiver output as

$$p_1(D) = \frac{1}{2\sigma^2}\left(\frac{D}{s^2}\right)^{(n-2)/4} e^{-(s^2+D)/2\sigma^2} I_{(n/2)-1}\left(\sqrt{D}\frac{s}{\sigma^2}\right) \quad (9)$$

where the n degree non-central chi-square distribution with s^2 mean and variance σ^2 and $I_\alpha(x)$ is the α th-order modified Bessel function of the first kind [6].

The probability of false alarm, P_{fa}, is defined as the probability that a sample *D(i)* will exceed the defined threshold when noise alone is present in the radar receiver,

$$P_{fa} = \int_T^\infty \frac{1}{\sigma^n 2^{n/2}\Gamma\left(\frac{1}{2}n\right)} D^{(n/2)-1} e^{-D/2\sigma^2} dD \quad (10)$$

where the n degree is the same as the *N* coherent integration number and *T* is the defined threshold level. The probability of detection, P_D, is the probability that a sample *D(i)* will exceed the defined threshold in the case of noise plus signal in the radar receiver,

$$P_D = \int_T^\infty \frac{1}{2\sigma^2}\left(\frac{D}{s^2}\right)^{(n-2)/4} e^{-(s^2+D)/2\sigma^2} I_{(n/2)-1}\left(\sqrt{D}\frac{s}{\sigma^2}\right) \quad (11).$$

The relation between the detection probability and the false alarm rate of the squared non-coherent receiver is analyzed with *N* non-coherent integration, as in Eq. (12) in Ref. 5.

$$\begin{aligned} P_D &= Q(Q^{-1}(P_{FA}/2) - \sqrt{N \cdot SNR}) \\ &+ Q(Q^{-1}(P_{FA}/2) + \sqrt{N \cdot SNR}) \end{aligned} \quad (12)$$

Eq. (12) represents the detection performance of the TR-FMCW-UWB radar receiver because we assume that the received signal passing through the delay block and the multiplier has the same distribution characteristic as that of the square of the Gaussian random variable.

4 Simulation results

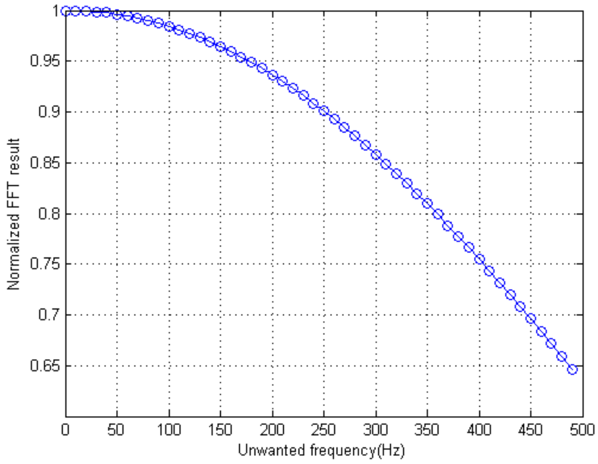

Figure 3. FFT results with effects of unwanted frequency

This section presents the detection probability of the proposed TR-FMCW-UWB radar receiver compared to that of the coherent receiver. The TR-FMCW-UWB system parameters are T=1 ms, B=1 GHz. The frequencies of the signals reflected from 1 m and 1.15 m for the TR-FMCW-UWB radar are 6.67 KHz and 7.67 KHz, respectively. We evaluate the coherent receiver according to unwanted frequency. The detection probability of the FMCW-UWB radar is determined by the FFT results according to the unwanted frequency, as shown in Fig. 3.

Fig. 4 shows the simulated detection performance for the proposed TR-FMCW-UWB receiver and for the coherent receiver according to unwanted frequency. As is well known, the proposed receiver requires about 1 dB more SNR than the ideal coherent receiver at the P_D of 0.5. However, the performance of the coherent receiver has an effect on the unwanted frequency. Fig. 4 shows the FFT results based on unwanted frequency. For P_D of 0.5, as shown in Fig. 3, the coherent receiver requires a higher SNR than does the proposed receiver when the unwanted frequency is 140 Hz.

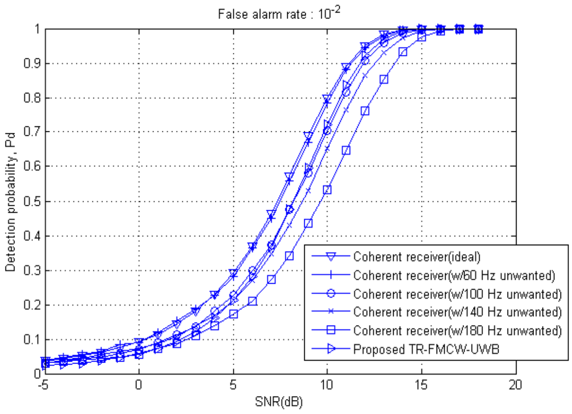

Figure 4. Detection probability of the proposed radar compared to that of the coherent receiver according to unwanted frequency

5 Conclusions

We have proposed a new TR-FMCW-UWB radar using a transmitted signal and a reference signal for use as a gasoline level gauge radar; this device is unaffected by unwanted signals such as Doppler frequencies. The TR-FMCW-UWB radar receiver is composed of an FFT block, a delay block, a multiplier, and an integrator block. The received signal becomes a sinusoidal signal when passing through the stretch processor. The sinusoidal received signal is detected by the proposed receiver regardless of distortion of the signal due to the unwanted frequency. Simulation results have shown that the proposed receiver provides better detection performance than that of an ideal coherent receiver in terms of unwanted frequency. In particular, when $P_D = 0.5$ and f_D = 140 Hz, the SNR of the proposed receiver has a detection performance better than that of a coherent receiver. In the future, the proposed receiver can be applied in various level gauge radars.

6 Acknowledgments

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7 References

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