Adaptive Self-Interference Cancellation System for Microwave LFMCW Radar with Optimal Delay Matching

Yunshuo Zhang, Qing Wang, Huanding Qin, Jin Meng
National Key Laboratory of Science and Technology on Vessel Integrated Power System
Naval University of Engineering
Wuhan, Hubei, 430033, China
E-mail: gudaowork@163.com

***Abstract*—Self-interference due to transmission power leakage to the receiver is a known problem for linear frequency modulated continuous wave (LFMCW) radar. To solve this problem, we propose an analog adaptive interference cancellation system based on down-conversion adaptive control. Specifically, the microwave signals, including the reference signal and the error signal, are first down-converted into ultra-short bands and then used to calculate the filter coefficients. To further improve the performance, we also propose a simple method to match the delays between the cancellation signal path and the interference signal path, by using only S-parameters. Experiments are conducted to evaluate our methods. The results show that interference cancellation ratio(ICR) can be as high as 35dB for a 150MHz bandwidth, which excel the peers in the literature.**

***Keywords*—self-interference; adaptive interference cancellation; LFMCW Radar; delay matching; channel dispersion**

I. Introduction

Linear frequency modulated continuous wave (LFMCW) radar has to transmit and receive simultaneously, therefore, certain measures have to be taken to avoid self-interference, i.e., the interference from the transmitter to its own receiver [1]. To overcome this problem, independent transmitting and receiving antennas are often used. A certain level of isolation can be obtained due to the antenna spacing, thereby reducing the self-interference. But when the space of the platform is small, the isolation provided is often insufficient [2]. Others ways to increase the isolation between the transmitting and receiving antenna is therefore needed.

An effective means to mitigate the self-interference is to utilize adaptive interference cancellation technique. The principle is to generate a cancellation signal which has opposite phase and equal amplitude with the interference signal, then add the cancellation signal with the received signal to suppress the interference. The method has been successfully applied to cancel the LFMCW radar self-interference, e.g., [2][3][4]. The frequency bands considered in these works are mostly the Ka-bands, however, we focus on microwave bands in this paper. The reported interference cancellation ratio (ICR) is usually lower than 30dB. In addition, only a single sweeping period is considered. However, as we will see later, the sweeping period is related to the cancellation performance. Therefore, it is hard to know if the same performance can be achieved for a wide range of LFMCW radar parameters.

In this paper, an analog adaptive interference cancellation system based on down-conversion adaptive control is proposed to solve the self-interference problem, and the S-parameters of the cancellation signal path and the interference signal path are only used to match the delays. Then for the analysis of the cancellation effect we carry out experiments under wired and wireless conditions, and a 35dB of ICR is achieved for a 150MHz band width.

The rest of the paper is organized as the follows. Section II describes in detail the interference cancellation system followed by a mathematical model and the proposed method for delay matching. Section III presents the experiment results. Conclusions are drawn in Section IV.

Corresponding author: Qing Wang,
Naval University of Engineering. Email: qwangwork@163.com

II. System Model

A. Adaptive Self-Interference Cancellation System

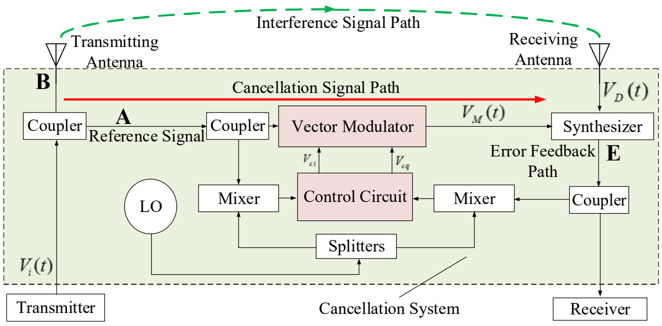


Fig. 1. Basic structure of interference cancellation system.

The basic structure of the microwave interference cancellation system based on the down-conversion adaptive control is shown in Fig. 1. In order to eliminate the self-interference signal which is the signal directly coupled from the transmitting antenna. A reference signal is coupled from the transmitter, of which the amplitude and phase are adjusted by a vector modulator to obtain a cancellation signal that has an opposite phase and equal amplitude of the received self-interference signal [5]. Finally, the interference signal is canceled in synthesizer by cancellation signal, the error signal is fed back to the weight control circuit through the error feedback path to optimize the weights of the output.

The signal from the transmitter is given as

$$V_i(t) = \cos(2\pi f_i t) \quad (1)$$

where $f_i = f_0 + \frac{B}{T_m} t$, is the ith frequency within a sweep period, B is the sweep bandwidth, T_m is the sweep period. The interference signal is then given by

$$V_D(t) = K_1 \cos[2\pi f_i (t + \frac{l_1}{v} + \frac{l_2}{c})] \quad (2)$$

where K_1 is the transmission coefficient from the transmitter to the receiver, l_1 is the electrical length from the transmitter to the transmitting antenna, l_2 is the distance from the transmitting antenna to the receiving antenna, v is the transmission speed of electromagnetic waves in the micro-strip line, c is the speed when electromagnetic waves travel in the air. The RF signal of the mixer can be expressed as

$$V_{RF}(\mathrm{t}) = K_1 K_2 \cos[2\pi f_i (t + \frac{l_1 + l_3}{v} + \frac{l_2}{c})] \quad (3)$$

In the equation, K_2 is the transmission coefficient from the antenna to the mixer, l_3 is the electrical length between combiner and coupler. The local oscillator signal is given as

$$V_{LO} = K_3 \cos[2\pi f_s (t + \frac{l_4}{v})] \quad (4)$$

where K_3 is the transmission coefficient from the transmitter to the mixer, f_s is the frequency of local oscillator, l_4 is the electrical length between the transmitter and the mixer. The RF signal and the local oscillator signal are mixed in mixer, and then down-converted by multiplier to get intermediate frequency control signals, which are given by

$$V_i(t) = LK_1K_2K_3u(t)\cos[2\pi(f_i - f_s)t + \theta] \quad (5)$$

$$V_q(t) = LK_1K_2K_3u(t)\sin[2\pi(f_i - f_s)t + \theta] \quad (6)$$

where L is the conversion loss of the mixer, $\theta{=}2\pi f_i(\frac{l_1 + l_3}{v} + \frac{l_2}{c}) - 2\pi f_s \frac{l_4}{v}$ is the phase of control signals. The control signal of the vector modulator can be calculated by the output of the mixer which is given by

$$V_{ci} = LK_1K_2K_3K_4 \cos[2\pi(f_i - f_s)t + \theta] \quad (7)$$

$$V_{cq} = LK_1K_2K_3K_4 \sin[2\pi(f_i - f_s)t + \theta)] \quad (8)$$

K_4 is the transmission coefficient of the weight control circuit. The RF input signal of the vector modulator is then given by

$$V_{MI}(t) = K_5\cos[2\pi f_i(t + \frac{l_5}{v})] \quad (9)$$

$$V_{MQ}(t) = K_5\sin[2\pi f_i(t + \frac{l_5}{v})] \quad (10)$$

In the equation, K_5 is the transmission coefficient from the transmitter to the vector modulator, l_5 is the electrical length from the transmitter to the vector modulator. The cancellation signal generated under I , Q control is given as

$$V_M(t) = \frac{\sqrt{2}}{2}[V_{MI}(t + \frac{l_6}{v}) \cdot K + V_{MQ}(t + \frac{l_6}{v}) \cdot K'] \quad (11)$$

where $K = M \cdot V_{ci}(t)$, $K' = M \cdot V_{cq}(t)$, M is the modulation coefficient of the vector modulator.

To examine the cancellation performance of the microwave adaptive interference cancellation system, define the interference cancellation ratio (ICR) as

$$ICR = 10\log_{10}\frac{P_I}{P_e} \quad (12)$$

where p_I is the power of the interference signal, p_e is the power of the residual interference signal after cancellation. Then the ICR is obtained as

$$ICR = 10\log_{10}\frac{|V_D(\mathrm{t})|^2}{|V_D(\mathrm{t}) + V_M(t)|^2} \quad (13)$$

In order to get a good cancellation effect, $V_M(t)$ needs to have opposite phase and equal amplitude with the $V_D(t)$. Compare $V_M(t)$ with $V_D(t)$, the sufficient conditions to obtain the ideal cancellation effect are given by

$$LMK_1K_2K_3K_4K_5 = \text{-}K_1 \quad (14)$$

$$\frac{l_6 + l_5}{v} = \frac{l_1}{v} + \frac{l_2}{c} \quad (15)$$

$$\frac{l_4}{v} = \frac{l_1 + l_3}{v} + \frac{l_2}{c} \quad (16)$$

These equations express that to achieve desired cancellation effect, the transmission coefficients and the electrical lengths passing through of $V_M(t)$ and $V_D(t)$ should be equal. And the electrical lengths of the mixing signals entering the two ends of the mixer should also be equal. (14) to (16) are important basis for designing cancellation system.

B. Optimal Delay Matching

From the last subsection, we know that the delay between the cancellation signal path and the interference signal path should be properly matched to get better performance. As it shown in Fig.1, the mismatching is due to the different paths and components the transmitting signals propagate through [6]. Therefore, it is necessary to match time delay on the cancellation signal and the interference signal to improve the cancellation performance.

Reference [7] proposed a method that using the frequency response (i.e. the S21 parameter) of interference path and reference path in microwave interference cancellation system to calculate the optimal weight and ICR. The method can be also used to find the delay matching problem here. Specifically, a delay τ of the reference signal (or the received signal) corresponds to a frequency response $e^{-j2\pi f\tau}$. Changing the delay is equivalent to changing the corresponding frequency response.

Use vector network analyzer to measure the S21 parameter of the reference path $H_{r0}(f_k)$ on points A and E in Fig.1, the S21 parameter of the interference path $H_i(f_k)$ on points B and E. Assume the reference path delay time is increased by τ based on the existing cancellation system. Then we can get the new S21 parameter of reference path as

$$H_r(f_k) = H_{r0}(f_k)\cdot\delta(\tau) \tag{17}$$

The optimum weight and the ICR are already derived in [7],

$$w_{opt} = \left(\sum_k H_r(f_k)H_r^H(f_k)\right)^{-1}\sum_k H_r(f_k)H_i^*(f_k) \tag{18}$$

$$ICR = 10\log_{10}\frac{\sum_k |H_i(f_k)|^2}{\sum_k |H_i(f_k) - w_{opt}^H H_r(f_k)|^2} \tag{19}$$

Then the optimal delay difference matching between the cancellation signal path and the interference signal path can be defined as

$$\tau_{opt} = \arg\max_{\tau} \text{ICR}(\tau) \tag{20}$$

III. Experiment Results

A. Simulation and Experiment under Wired Condition

In this section, we present simulation results to examine the estimate of optimal delay using S-parameters. Then the cancellation system is adjusted by referencing the results, and complete the wired interference coupling cancellation experiments.

The simulation results are given in Fig.2. The system theoretically has the best cancellation effect when the delay time difference between reference and interference paths is 0.29ns, which can reach 57.2 dB. However, it is difficult to realize this cancellation effect in circuit, because achieving accurate matching is tough. When delay matching is performed on the actual circuit, if the error is 0.1 ns compared with the optimal delay matching, the ICR can only reach 31dB. And the dispersion in signal propagation also reduces the cancellation performance.

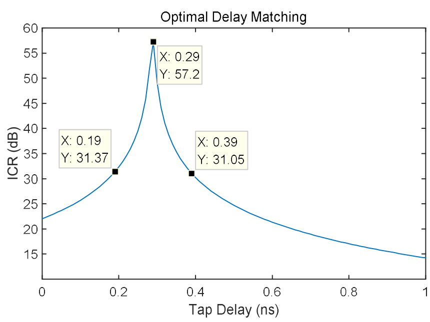


Fig. 2. Optimal delay matching result.

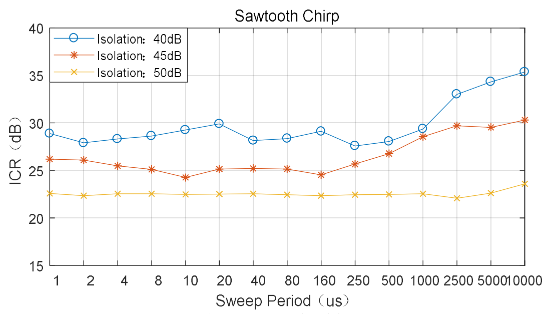
Then revise the circuit delay based on the above results and perform the following experiments under the wired interference coupling, which is an ideal condition by simulating the isolation between transceiver antennas through the adjustable attenuator. The parameters of the microwave interference cancellation experiment are shown in Table I.

TABLE I. EXPERIMENTAL PARAMETERS

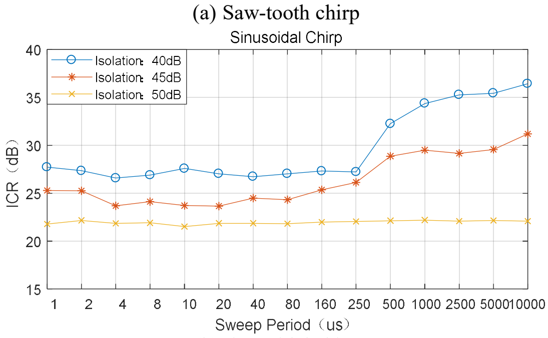
Center frequency	4.5GHz
Bandwidth	150MHz
Source power	23dBm（200mW）
Isolation	40, 45, 50dB

The results are shown in Fig. 3. Two examples of the interference spectrum before and after cancellation are given in Fig. 4. It can be seen that under 40dB isolation, the ICR of the system in the range of 1us~250us sweep periods are about 27dB~35dB. This is because the integration time for calculating controlling signals is fixed, which is optimal for a certain range of sweeping periods (here the large ones).

The experimental results also show that the cancellation performance is affected by the isolation, the higher the isolation between the antennas, the smaller the ICR, but the bigger the sum of them in small difference. And the ICR under the frequency modulation of saw-tooth wave and sine wave is consistent with the change of the sweep period.

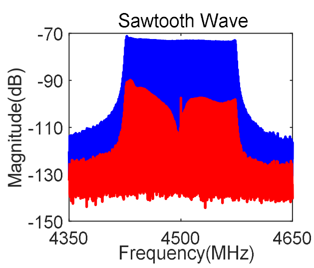


(a) Saw-tooth chirp

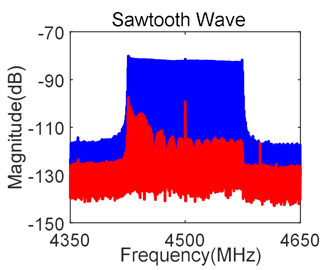


(b)Sinusoidal chirp

Fig. 3. Results of wired interference coupling experiments.



(a)Sweep Period：20us



(b) Sweep Period：160us

Fig. 4. Spectrum of the signal before and after cancellation.

B. Experiment under Wireless Condition

In order to simulate the working conditions of the LFMCW radar and reduce the near field interference, the wireless interference coupling experiments are carried out in open space field after delay matching, where the isolation between the antennas is 45dB. The wireless test system is shown in Fig. 5.

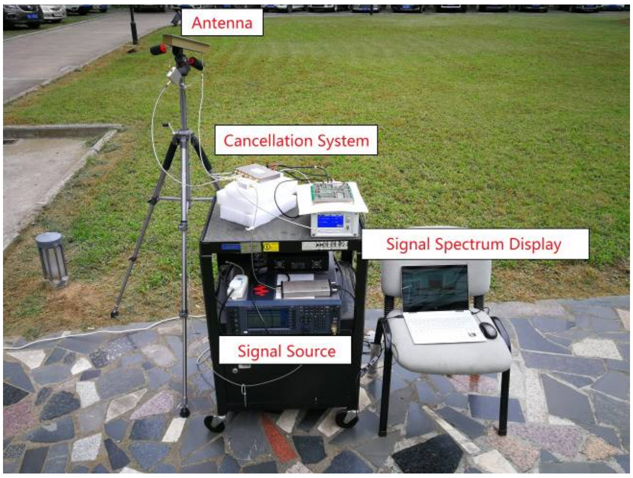


Fig. 5. Wireless test system.

The parameters of the wired and wireless interference coupling experiments are the same. The results are shown in Fig. 6. Two examples of the interference spectrum before and after cancellation are given in Fig. 7. As we can see, the performance is poorer than wired coupling, as the ICR is only about 16~25dB. The major reason is that the interference experiences stronger channel dispersion due to the spatial coupling between the transmit and receive antennas, in comparison with non-dispersive wired coupling.

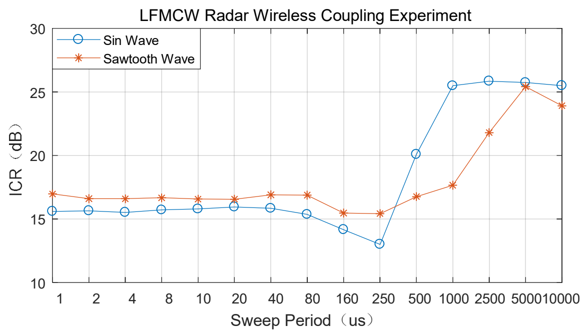
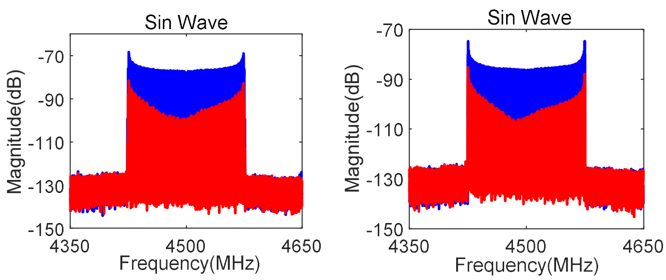


Fig. 6. Results of wireless interference coupling experiments.



(a)Sweep Period：20us (b)Sweep Period：160us

Fig. 7. Spectrum of the signal before and after cancellation.

IV. Conclusion

In this paper, we have proposed a microwave band self-interference cancellation system for mitigating the self-interference problem of LFMCW radar. We have also proposed a method to optimize the delays between the cancellation signal path and the interference signal path to achieve better cancellation performance. The proposed cancellation system is demonstrated via experiments. The results show that the ICR can be as high as 35dB for a 150MHz bandwidth under wired interference coupling condition, and 25dB under wireless coupling condition. However, the ICR is related to the sweeping period of the LFMCW signal due to the fixed integration time of the adaptive controller. In addition, delay matching under wireless coupling condition is difficult to optimize due to channel dispersion between the transmitting and receiving antennas especially for a large bandwidth. Further improvements can be achieved with a higher delay matching accuracy and reduction of the channel dispersion.

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