Experimental Comparison of Stepped Multiple Frequency CPC with Pulse Compression

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***Abstract*— Authors have developed the stepped multiple frequency Complementary Phase Code (CPC) radar system. The unique radar modulation/demodulation method can achieve both a high range resolution and a long-range detection performance with a narrow band receiver compared with the transmission bandwidth. In this paper, the experimental verification to compare the detection range performances between Stepped multiple frequency CPC and Pulse compression was conducted. The experimental results indicated that the proposed modulation was 1.72 times superior to Pulse compression in the detection range performance on the condition where the transmission bandwidth, observation time, peak power, code length (the number of chips of switching codes), and the number of total pulses were set to be the same.**

Keywords*— Radar; Stepped Multiple Frequency CPC; Pulse compression; Detection range performance

I. Introduction

Frequency Modulation Continuous Wave (FMCW) radar, which provides a high range resolution with relatively low computation load, is widely employed for current automotive radar systems. However, the miss-pairing of the detected beat-frequency in the up and down sweeps of FMCW tend to cause a problem under the multiple target situations in principle [1].

Pulse compression [1] is another common technique to realize a high range resolution equivalent to the transmission bandwidth without the pairing process. Meanwhile pulse compression generally needs the wide band receiver to accomplish the high range resolution, which decreases S/N ratio and requires a heavy computational load.

Authors have been developing the millimeter wave radar using stepped multiple frequency Complementary Phase Code (CPC) [2]. The unique radar modulation/demodulation method can achieve a high range resolution and a long-range detection performance by a narrow receiver's bandwidth compared to the transmission bandwidth. We have previously demonstrated that the prototype radar operated in 60GHz band using the modulation satisfied the expected performance of the sidelobe and the range resolution [2].

In this paper, the experimental verification to compare the detection range performance between Stepped multiple frequency CPC and Pulse compression modulations was conducted in an anechoic chamber under the situation where the transmission bandwidth, observation time, peak power, and code length (number of switching phase codes) were set to be the same among them. Author employs Software radar [3] that can produce any shape of waveforms designed by operators for the experiments conducted in this research.

II. Pulse compression radar

In this chapter, we will describe Pulse compression radar which employs Pulse Doppler Filter (PDF). Pulse compression allows us to achieve a range resolution equivalent to the transmission bandwidth. As shown in Fig.1 (a), the pulse compression radar generally transmits relatively long Linear Frequency Modulated (LFM) or phase coded pulses. In this paper, we employ phase coded pulses using P4 code. The range resolution equivalent to the transmission bandwidth and the S/N improvement are obtained by the signal processing on the received signals.

A. Block diagram of signal processing of pulse compression

Fig.1 (b) shows the block diagram of signal processing of Pulse compression radar. The received signal is sampled by an A/D converter (ADC) after being mixed by the transmission carrier waveform and passing Low Pass Filter (LPF). The pulse compression process (PC) is done for each Pulse Repetition Interval (PRI). After PC, PDF is performed on the same range bin in pulse hit direction. Eventually we can obtain the target range and velocity (Range-Doppler map).

B. Signal processing of pulse compression radar

Since the matched filter is a linear time invariant system, its output can be described mathematically by the convolution between the received signal $R(t)$ and reference signal $Ref(t)$, which is called pulse compression. The reference signal is the time inverse complex conjugate of the transmission pulse.

$$PC(t) = \int_{t_1}^{t_2} R(\tau) Ref(t-\tau) d\tau \qquad (1)$$

Practically, this process is performed by the multiplication of the received signal and reference signal in the frequency domain from the point of view of the computational load. The PC process can be also described by (2).

$$PC[s] = \Im^{-1}(\Im(R) \cdot \Im(Ref)) \qquad (2)$$

where $\Im$ and $\Im^{-1}$ is the FFT and inverse FFT, respectively.

After PC, PDF is performed on the same range bin in pulse hit direction (*m* direction in Fig.1 (a)), which is described by (3). Then power spectrum is obtained associated with range bin *s* and Doppler frequency bin *k*.

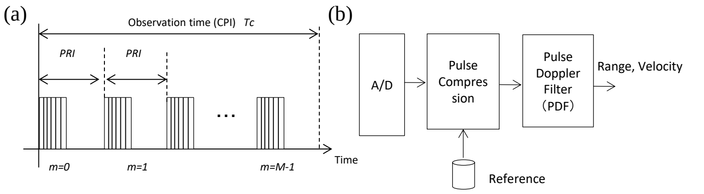

Fig. 1 The modulation/demodulation of Pulse compression radar ((a) transmission sequence, (b) block diagram of signal processing)

$$PD[k,s] = \sum_{m=0}^{M-1} PC[m,s] \cdot \exp\left(-2\pi j \cdot \left(\frac{m}{M} k\right)\right) \quad (3)$$

Here, the Doppler frequency is denoted by using Doppler frequency bin as following relationship.

$$fd = \frac{k}{2 \cdot T_{PRI} \cdot N \cdot M} \quad (4)$$

C. S/N improvement by the signal processing

The signal processing of pulse compression radar is composed of PC and PDF. The S/N improvement by the signal processing is expected as described by (5), since the signal processing is coherent processing.

$$SNI = 10\log_{10}(P) + 10\log_{10}(M) \quad (5)$$

where P and M are the number of the chip of switching P4 codes and the number of pulses, respectively.

III. STEPPED MULTIPLE FREQUENCY CPC RADAR

Stepped multiple frequency CPC modulation is a hybrid method of synthetic bandwidth (Synthetic Wideband Waveform (SWW)) [4] and pulse compression. In addition, this method adopts CPC pulses for the pulse compression. As shown in Fig.2 (a), the pair of CPC pulses which satisfy the complementary condition each other are coded on the same carrier frequency. The transmitted carrier frequencies are changed N times step-like in a sequence. The same sequences are repeated M times.

A. Block diagram of signal processing of Stepped multiple frequency CPC radar

Fig.2 (b) shows the block diagram of the signal processing of Stepped multiple frequency CPC. After PC process, Doppler frequencies which correspond to the relative velocities of targets are estimated by FFT in pulse hit direction m on the same range bin. This process is equivalent to PDF of Pulse compression radar. The CPC pulse compression that is the combination of Pulse compression, Compensation of Doppler shift, and ADD process provides the range gate for the subsequent Synthetic Wideband Waveform (SWW) with extremely low range side-lobe. Finally, SWW produces Range-Doppler map with a high range resolution equivalent to the transmission bandwidth by a narrow band receiver compared with the transmission bandwidth.

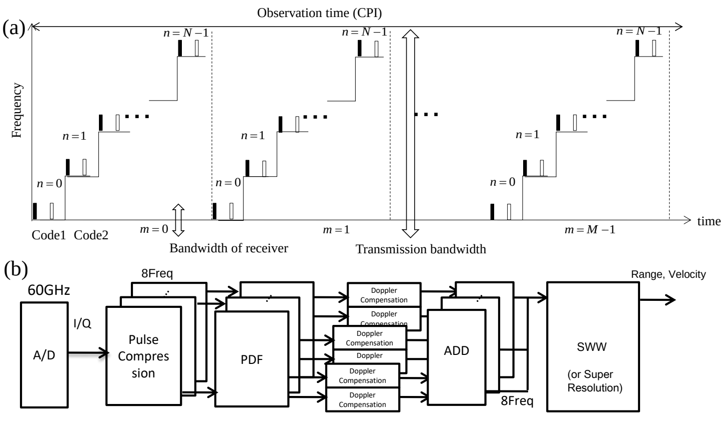

Fig. 2 The modulation/demodulation of Stepped multiple frequency CPC radar ((a) transmission sequence, (b) block diagram of signal processing)

B. Signal processing of Stepped multiple frequency CPC radar

As in the case with Pulse compression radar, PC is done for each PRI. That is denoted by the function of sequence number m and frequency step n, and complementary code *code*, and range bin s.

$$PC[code,n,m,s] = \Im^{-1}(\Im(R) \cdot \Im(Ref)) \quad (6)$$

PDF is also performed in sequence direction (m direction in Fig.2 (a)) on the same range bin, which is described by (7).

$$PD[code,n,m,s] = \sum_{k=0}^{M-1} PC[code,n,m,s] \cdot \exp\left(-2\pi j \cdot \left(\frac{m}{M} k\right)\right) \quad (7)$$

CPC pulse compression generally suffers from the phase shift due to the Doppler frequency. Stepped multiple frequency CPC has the compensation process for the phase shift.

$$PHC[code,n,m,s] = PD \cdot \exp\left\{2\pi j \frac{m}{2MN \cdot PRI}\left(s + PRI \cdot (2n + code)\right)\right\} \quad (8)$$

After the phase compensation process, CPC pulse compression is completed by ADD process where the output of code 1 is added by that of code 2.

$$ADD[n,m,s] = \sum_{code=0}^{1} PHC[code,n,m,s] \quad (9)$$

As a result, the range profile has extremely low range side-lobe. Finally, SWW, which is realized by FFT in frequency direction (n direction) produces a high range resolution equivalent to the transmission bandwidth by a narrow band receiver compared with the transmission bandwidth.

$$SWW[m,s'] = \sum_{n=0}^{N-1} ADD[n,m,s] \exp\left(j \cdot \left(\frac{4\pi \cdot s' \cdot \Delta R}{c} n \cdot \Delta f\right)\right)$$
$$s' = N \cdot s + n \quad (10)$$

We have an option to obtain range profile corresponding Doppler bin with higher resolution by using super resolution method for the short range instead of SWW [5], which we call Super Resolution mode.

C. S/N improvement by the signal processing

The signal processing of stepped multiple frequency CPC radar is composed of PC, PDF, ADD, and SWW. The S/N improvement by the signal processing is given by (11), since these are all coherent processing.

$$SNI = 10\log_{10}(P) + 10\log_{10}(M) + 10\log_{10}(2) + 10\log_{10}(N) \quad (11)$$

IV. EXPERIMENTAL VERIFICATION (CASE I)

The first experimental verification is conducted on the condition (case I) where the number of frequency step is set to be 16, which allows us reduce the bandwidth of the receiver to1/10. Then the other condition (case II) where the number of frequency step is set to be 8, which is adopted by the millimeter wave radar using stepped multiple frequency CPC. On the experiments, the transmission bandwidth, observation time (CPI), peak power of transmission, code length (number of chips of switching codes), and the number of total pulses are set to be same between Pulse compression and Stepped multiple frequency CPC.

A. Radar parameters and the condition of the experiment

Tables 1 and 2 shows the radar parameters of Pulse compression and Stepped multiple frequency CPC, respectively. We use a corner reflector as a target which has 10dBsm of RCS and is moved between 15.44m and 17.04m at the radial velocity of 4km/h by an actuator. The experiment is conducted in an anechoic chamber (24m×15m×10m).

B. S/N expectation of Pulse compression and Stepped multiple frequency CPC

The S/N improvement by the signal processing of Pulse compression is calculated as 54.18dB by (5), where P and M are 16 and 16384, respectively as shown in table 1. The S/N improvement of Stepped multiple frequency CPC is also obtained as 54.18dB by (11), where P, M, and N are 16, 512, and 16, respectively as shown in table 2. Therefore the S/N improvement by the signal processing is the same between both modulation methods. On the other hand, at the input of ADC, S/N of Stepped multiple frequency CPC is expected to be 10dB superior to that of Pulse compression due to the difference of the receiver's bandwidth. We would like to note that on the experiments we used 0-90MHz and 0-20MHz LPFs, respectively. The S/N expected to be obtained by using the ideal LPFs (* in Tables) is calculated by (12) and (13).

$$S/N(\text{converted}) = S/N(\text{obtained}) - 10\log_{10}\left(\frac{100}{90}\right) \quad (12)$$

$$S/N(\text{converted}) = S/N(\text{obtained}) + 10\log_{10}\left(\frac{20}{10}\right) \quad (13)$$

C. Experimental Results

Fig.3 shows a result of Range-Doppler map of Pulse compression and Stepped multiple frequency CPC, respectively. In the Fig. 3 (a), a peak associated with the target (16.32m, 3.89km/h) is identified. In the Fig. 3(b), a peak associated with the target (16.22m, 3.89km/h) is also identified. The S/N is obtained by the ratio of the peak power and the noise level. The S/N in the case of Pulse compression and Stepped multiple frequency CPC are obtained as 60.09 dB (@16.32m) and 66.45 dB (@16.22m), respectively. These results are equivalent to 108.59 dB and 114.85 dB at the range of 1m. Eventually we can obtain converted S/N 108.13 dB and 117.86 dB by (12) and (13).

The experiments described above are conducted 50 times for Pulse compression and Stepped multiple frequency CPC. These results are summarized in Table 3. From Table 3, it is indicated that S/N of Stepped multiple frequency CPC is 9.45 dB superior to that of Pulse compression. That means that the proposed modulation is 1.72 times superior to PC in the detection range performance on the experimental condition.

TABLE 1 Radar Parameters of Pulse compression in Case I

Parameters	Specifications
Transmission frequency f_0	24.15GHz
Pulse Bandwidth B	50MHz
Switching phase time T_{chip}	20ns
Number of chips of switching codes (code length) P	16
Pulse repetition Interval（PRI）	5.6μs
Number of pulses M	16384
Transmission Bandwidth B	50MHz
Observation time (CPI) Tcpi	91.75ms
A/D Sampling frequency *fs*	180MHz
Bandwidth of LPF	0-100MHz（*）
Range resolution ΔR	3m
Velocity resolution	0.241km/h

TABLE 2 Radar Parameters of Stepped multiple frequency CPC in Case I

Parameters	Specifications
Transmission frequency f_0	24.1275GHz
Pulse Bandwidth b	5MHz
Switching phase time T_{chip}	200ns
Number of chips of switching codes (code length) P	16
Pulse repetition Interval (PRI)	5.6μs
Number of pulses (Number of sequence) M	512
Frequency step width Δ*f*	3MHz
Number of frequency step N	16
Transmission Bandwidth B	50MHz
Observation time (CPI) Tcpi	91.75ms
A/D Sampling frequency *fs*	180MHz
Bandwidth of LPF	0-10MHz（*）
Range resolution ΔR	3m
Velocity resolution	0.241km/h

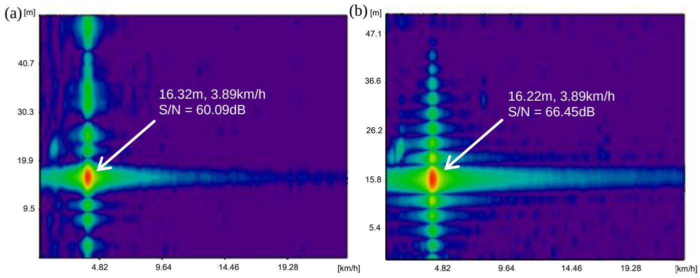

Fig. 3 Range Doppler map obtained from two methods in Case I ((a) Pulse compression, (b) Stepped multiple frequency CPC)

TABLE 3. S/N at the range of 1m of two methods in Case I

	S/N @ 1m[dB]	Standard deviation	S/N @1m (converted) [dB]
Pulse compression (Case I)	108.62	0.55	108.16
Stepped multiple frequency CPC (Case I)	114.60	0.38	117.61

V. EXPERIMENTAL VERIFICATION (CASE II)

In this section, the experimental verification results are shown where the number of frequency step is set to be 8, which is adopted by the millimeter wave radar using stepped multiple frequency CPC developed by authors [2]. In addition the radar system also has Super Resolution mode for short range. The super resolution method such as MUSIC is used instead of SWW.

A. Radar parameters and the condition of the experiment

Tables 4 and 5 show the radar parameters of Pulse compression and Stepped multiple frequency CPC, respectively. The target condition is same as in the case I.

B. *S/N expectation of Pulse compression and Stepped multiple frequency CPC*

The S/N improvement by the signal processing of Pulse compression and Stepped multiple frequency CPC are calculated as 51.18dB by (5). At the input of ADC, S/N of Stepped multiple frequency CPC is expected to be 7dB superior to that of Pulse compression due to the difference of the receiver's bandwidth. The S/N of Pulse compression expected to be obtained on the experiment is converted by (12) from the same reason of case I.

C. *Experimental Results*

Fig.4 shows an example of the result of Range-Doppler map of two methods. The S/N in the case of Pulse compression and Stepped multiple frequency CPC are obtained as 59.41 dB and 64.10 dB, respectively. These results are equivalent to 107.92 dB and 112.50 dB at the range of 1m. Eventually we can obtain converted S/N 107.46 for Pulse compression by (12). On the other hand, no conversion is needed for Stepped multiple frequency CPC in Case II.

The results conducted 50 times are summarized in Table 6. From Table 6, it is indicated that S/N of Stepped multiple frequency CPC is 5.27 dB superior to that of Pulse compression, which is equivalent to 1.35 times superior to Pulse compression in the detection range performance.

Fig.5 shows the results of Super Resolution mode of Stepped multiple frequency CPC. In the experiments of Super Resolution mode, we used two corner reflectors that are moved at same velocity and are separated with 3.0m and 1.5m, which are equivalent to range resolution ΔR and 1/2ΔR, respectively. For two cases, the experiments are repeated 30 times. In all experiments, Super Resolution mode could isolate the two targets.

TABLE 4 Radar Parameters of Pulse compression in Case II

Parameters	Specifications
Transmission frequency f_0	24GHz
Pulse Bandwidth B	50MHz
Switching phase time T_{chip}	20ns
Number of chips of switching codes (code length) P	16
Pulse repetition Interval（PRI）	4.0μs
Number of pulses M	8192
Transmission Bandwidth B	50MHz
Observation time (CPI) Tcpi	32.77ms
A/D Sampling frequency *fs*	180MHz
Bandwidth of LPF	0-100MHz（*）
Range resolutionΔR	3m
Velocity resolution	0.682km/h

TABLE 5 Radar Parameters of Stepped multiple frequency CPC in Case II

Parameters	Specifications
Transmission frequency f_0	24.13GHz
Pulse Bandwidth b	10MHz
Switching phase time T_{chip}	100ns
Number of chips of switching codes (code length) P	16
Pulse repetition Interval (PRI)	4.0μs
Number of pulses (Number of sequence) M	512
Frequency step width Δ*f*	5.715MHz
Number of frequency step N	8
Transmission Bandwidth B	50MHz
Observation time (CPI) Tcpi	32.77ms
A/D Sampling frequency *fs*	180MHz
Bandwidth of LPF	0-20MHz
Range resolutionΔR	3m
Velocity resolution	0.682km/h

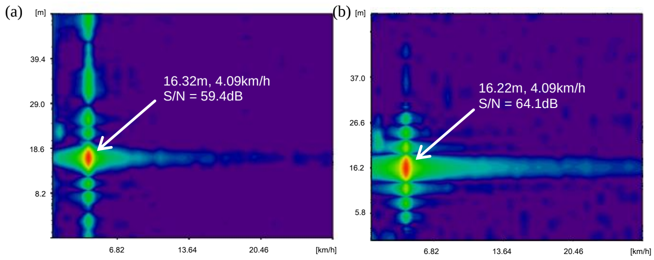

Fig. 4 Range Doppler map obtained from two methods in Case II ((a) Pulse compression, (b) Stepped multiple frequency CPC)

TABLE 6. S/N at the range of 1m of two methods in Case II

	S/N @ 1m[dB]	Standard deviation	S/N @1m (converted) [dB]
Pulse compression (Case II)	107.75	0.47	107.29
Stepped multiple frequency CPC (Case II)	112.56	0.32	112.56 (not converted)

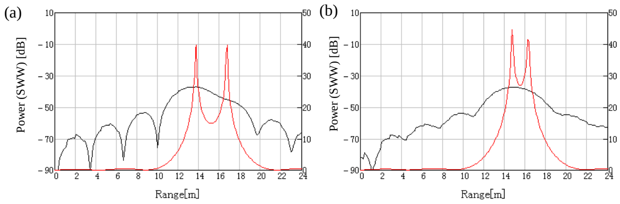

Fig. 5 Range profiles by SWW (black line) and Super Resolution mode (Red line) for 2 targets which have range differences. ((a) ΔR, (b) 1/2ΔR)

V. CONCLUSIONS

The experimental verification to compare the detectable range performances between Stepped multiple frequency CPC and Pulse compression was conducted in an anechoic chamber. As a result, it was indicated that the detection range performance of Stepped multiple frequency CPC was 1.72 times superior to that of Pulse compression on the condition where the transmission bandwidth, observation time, peak power, code length, and the number of total pulses were set to be the same . In addition we also showed the results of Super Resolution mode in Stepped multiple frequency CPC.

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