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Development of Millimeter wave Radar using Stepped Multiple Frequency Complementary Phase Code modulation

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Abstract This paper describes a development of Millimeter wave Radar (Experimental model) for automotive and railway safety monitoring system. The radar is based on Stepped multiple-frequency CPC(complementary phase code) that is our proposed radar signal modulation to obtain high range resolution with the narrowband receiver. In this paper, the Stepped multiple frequency CPC modulation is explained. Next, the development procedures and the radar configuration is presented. Furthermore, it is shown that the expected good range resolution performance by Stepped multiple-frequency CPC is also obtained by means of experimental study using 24GHz off-line radar in anechoic chamber.

Keyword Radar, Pulse Compression, Step Frequency

1. Introduction

The radar technology has been applied for the meteorological observation and the air traffic control and the military equipment, etc. In recent years, the short range radar is expected to be utilized for the automotive radar in Intelligent Transport System, and the railway safety monitoring system which detects the human having fallen onto tracks from a platform and the obstacles in the railway crossing. In case of millimeter wave automotive radar, it is required to provides the function such as Adaptive Cruise Control (ACC) (detection distance of 150m or more) and Stop and Go[1].In general, FMCW(Frequency Modulated Continuous Wave) modulation which provide a high range resolution with less signal processing complexity compared to a pulse compression radar is adopted for millimeter wave automotive radar.

However, the miss-pairing of the detected beat-frequency in the up sweep and the down sweep of FMCW is serious problems under the multi target environment. Furthermore, the fact that transmission waves are CW system results in transmission/reception isolation problems as well as a problem of reflected wave(clutter) from needless reflective objects at short ranges with a small propagation loss. One effective measure to avoid these problems in FMCW is an FMICW(FM Interrupted CW) that switches between transmitting and receiving.

The authors proposed a moving target detection system in FMICW[2], used up to the present time as well as interference suppressions that stagger PRI[3]. The required occupied transmission frequency bandwidth in an FMCW or FMICW is identically wideband to a pulse compression method and linear FM sweep with high accuracy must be generated that extends to bandwidth $B=c/2\delta R$ (c is the velocity of light) in order to obtain range resolution of δR. In the above mentioned technical background, Stepped Multiple Frequency Interrupted CW modulation was presented in our previous study[4]. The modulation can obtain a short observation time compared to a conventional up/down sweep FMCW system or a two-frequency CW system with less computational complexity than a two-dimensional super resolution system by using a new transmission frequency sequence intended for short-range targets and a single-dimension super-resolution system that preprocesses a target velocity detection process through the use of an ordinary Fourier transformation. However, the problem of this method is range ambiguity, since the target distance is obtained by means of measuring of the received signal's phase difference in dependence of transmission frequencies.

For this purpose, we propose to enhance the method to Stepped multiple frequency complementary phase code(CPC)[5][6][7][8] which employs intra-pulse phase coded by CPC in order to divide the distance by range gates processed by CPC pulse compression. The CPC pulse compression by adding two complementary codes with correction of Doppler shift by Pulse Doppler processing provides the superior range gate with extremely low range sidelobes. Between each range gates, the high range resolution is obtained, through the use of flourier transformation into the detected Doppler spectrum of each pulse compressed signal with the received stepped frequency signal.

In this paper, the principle of the Stepped multiple frequency CPC modulation is presented. Furthermore, the development procedures and the outline of an experiment model radar with the Stepped multiple frequency CPC modulation in accordance with specified low-power radio station standard of the millimeter wave (transmitting power 10mW and transmitting bandwidth of 500MHz) are described. Even further, it is shown that the expected good range resolution performance by the Stepped multiple-frequency CPC is also obtained by an experimental study using 24GHz off-line radar in anechoic chamber.

2. Stepped multiple frequency CPC

The Stepped multiple frequency CPC modulation is characterized as follows.

①The transmission frequency sequence(in shown Fig.1) to which several transmit frequencies are switched by time division is used.

②In each transmit frequency, the pulses whose phases are modulated with Code1 and Code2 by satisfied the complementary condition to each other are transmitted alternately by PRI(Pulse Repetition Intervals).

Next, we explain the concept of the signal processing for the Stepped multiple frequency CPC which is based on the CPC pulse compression and the synthetic bandwidth processing. Though synthetic bandwidth processing provides high range resolution by a narrow receiver bandwidth and the comparatively low speed A/D,the observation time becomes long in general because the frequencies are switched by time division. Additionally the problems occur such as called range ambiguity. On the other hand, the transmit pulses modulate by the two complementary phase codes, and the pulse compression signal is used as a range gates to solve the range ambiguity problem.CPC can ideally achieve complete zero sidelobes. Nevertheless, under the influence of the Doppler shift, it is well known that the sidelobe level of the CPC pulse compression decreases and the range bias error in the synthetic bandwidth processing occurs respectively.

As a consequence, the signal processing is performed in the following order, complementary code pulse compression, pulse Doppler filter, Doppler compensation, complementary code addition and synthetic wideband processing. One of the notable features is that eight frequency steps are able to use for millimeter wave automotive radar application which requires the some hundred of meters in detection range, two hundred kilometer per hours in relative velocity and twenty Hz in data rate. Hence, receiver bandwidth and A/D performance are reduced to one eighth of the transmission frequency bandwidth which determine the final range resolution. The measurement signal and the signal processing about Stepped multiple frequency CPC will be described.

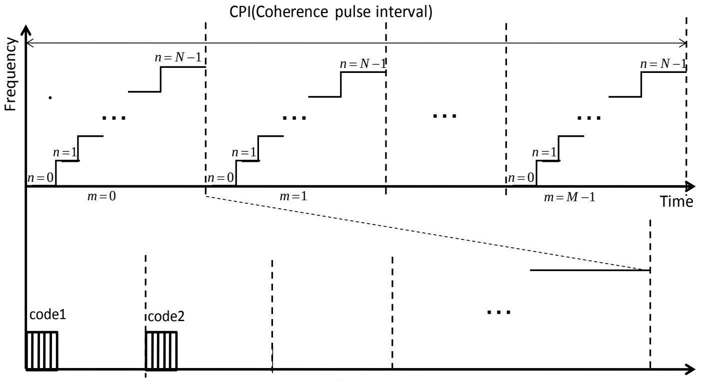

Fig.1 Transmission frequency sequence

2.1. Measurement signal of Stepped multiple frequency CPC

The measurement signal model for Stepped multiple frequency CPC will be described here. In transmission frequency sequence of Stepped multiple frequency CPC(shown in Fig.1),transmit frequency $f(n) = f + \Delta f \cdot n (n = 0 \ldots N-1)$ is switched every $2 \cdot T_{PRI}$ .In each transmit frequency, the pulse that exists in the relation of complementary is transmitted by T_{PRI} in order of Code1 and Code2.Here, Δf shows that frequency step width, f is beginning of transmit frequency. The transmission wave reflected per target reflects incident to the Rx antenna as a received wave after time delay τ that corresponds to the round-trip time of the target. The received wave is down-converted into baseband signal by means of mixing with the transmission wave f(n). The baseband signals of code1 and code2 in range bin (time delay τ) are given by Eq.(1)(2).

$$x(n, m, \phi 1) = \exp\left[j\left(2\pi f_d \cdot T_{PRI} \cdot 2N \cdot m + \left(2\pi f_d \cdot T_{PRI} \cdot 2 - \frac{4\pi\Delta f}{c}R\right) \cdot n - \frac{4\pi f}{c}R + 2\pi f_d \tau\right)\right] \exp(j\phi 1) \quad \ldots(1)$$

$$x(n, m, \phi 2) = \exp\left[j\left(2\pi f_d \cdot T_{PRI} \cdot 2N \cdot m + \left(2\pi f_d \cdot T_{PRI} \cdot 2 - \frac{4\pi\Delta f}{c}R\right) \cdot n - \frac{4\pi f}{c}R + 2\pi f_d (T_{PRI} + \tau)\right)\right] \exp(j\phi 2) \quad \ldots(2)$$

Here, $f_d (= 2vf/c)$,is the Doppler frequency, v is the relative velocity and R is the range of target.$\phi 1$,$\phi 2$ denotes code1 and code2 respectively. When multiple targets exist, the measurement signal can be expressed as the linear sum of Eq.(1)(2).As understood from Eq.(1)(2),the target relative velocity is obtained from the sampling signal about variable m.It is also understood that the frequency of the n direction sampling is the function both of the range and the relative velocity.

2.2. Signal processing of Stepped multiple frequency CPC

In this section , it is explained the signal processing of Stepped multiple frequency CPC as shown in Fig2.The baseband digitized signal after the analog to digital conversion in each m, n, and codes is set into the pulse compression processing.

$$X(n, m, \phi) = IFFT[FFT[x(n, m, \phi)] \cdot FFT[h(n, m, \phi)]] \ldots(3)$$

Where, *h(n,m)* denotes the reference signal which is given by the complex conjugate of transmission code signal.

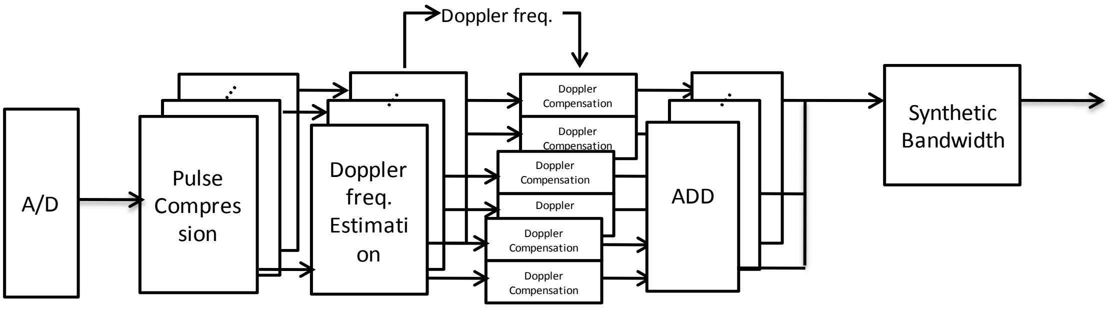

Fig.2 Schematic diagram of Stepped multiple frequency CPC

Next, in the pulse Doppler filter, the pulse compressed signal with each n and codes is processed by discrete Fourier transform in the direction of m.

$$\mathrm{F}(n,k,\phi) = \sum_{m=0}^{M-1} X(n,m,\phi)\cdot\exp\left[-2\pi\mathrm{j}\cdot\left(\frac{m}{M}k\right)\right] \qquad \dots(4)$$

Here, $\mathrm{k}(=0,1\dots\mathrm{M}-1)$ is a frequency channel number. The amplitude value $|\mathrm{F}(n,k,\phi)|$ after substituting Eq.(4) is the frequency channel number at each frequency step n.

$$\mathrm{k}_{peak} = f_d\cdot\mathrm{T}_{\mathrm{PRI}}\cdot M\cdot 2N \qquad \dots(5)$$

Then, it becomes a coherent integration and the peak is obtained. Thus, the target Doppler frequency is obtained by means of detecting the frequency channel number k_{peak} in which the output amplitude of Eq.(4) is the peak. The target relative velocity from the detected number k_{peak} is obtained from the equation.

$$\hat{\mathrm{V}} = f_d\cdot\frac{\lambda}{2} = \frac{\mathrm{k}_{peak}}{\mathrm{T}_{\mathrm{PRI}}\cdot M\cdot 2N}\cdot\frac{\lambda}{2} \qquad \dots(6)$$

In the next Doppler compensation, the phase difference of the detection frequency channel caused by the Doppler shift that depends on the gap of the phase, the time difference of each frequency step, and the time difference of each code are corrected by using the following Eq.(7)(8)

$$\mathrm{p}(n,k_{peak},\phi 1) =\cdot\exp\left[2\pi\mathrm{j}\left(\frac{\mathrm{k}_{peak}}{\mathrm{T}_{\mathrm{PRI}}\cdot M\cdot 2N}\cdot\mathrm{T}_{\mathrm{PRI}}\cdot 2n\right)\right] \qquad \dots(7)$$

$$\mathrm{p}(n,k_{peak},\phi 2) = \exp\left[2\pi\mathrm{j}\left(\frac{\mathrm{k}_{peak}}{\mathrm{T}_{\mathrm{PRI}}\cdot M\cdot 2N}\cdot\mathrm{T}_{\mathrm{PRI}}\cdot(2n+1)\right)\right] \qquad \dots(8)$$

Code1 and Code2 after the Doppler compensation are added. Finally, the synthetic bandwidth processing synthesizes the outputs of addition processing of each frequency step n through the use of Fourier transformation in the number n in each range bins.

$$\mathrm{R}(r) = \sum_{n=0}^{N-1} F(n)\cdot\exp\left[\mathrm{j}\left(\frac{4\pi f_n}{c}\right)\cdot r\right] \qquad \dots(9)$$

r is the steering distance that of the range depend on the range bins number. When the total transmission bandwidth is assumed to be B, the range resolution after a synthetic bandwidth processing is given by the following Eq.(10), although receiver bandwidth is almost equal to that of CPC pulse.

$$\Delta\mathrm{R} = \frac{c}{2B} \qquad \dots(10)$$

In the radar parameter in case of the millimeter wave automotive radar etc. The range bias error because of the Doppler shift in the pulse compression processing can be almost disregarded. Therefore, the Doppler compensation is performed after pulse compression.

3. Millimeter wave Radar using Stepped multiple frequency CPC

Millimeter wave Radar(Experimental model) based on the Stepped multiple frequency CPC is under development as shown the configuration in Fig.3.The radar which employs the radar parameter in table.3 meets specified low-power radio station standard of the millimeter wave(transmit frequency 60.0-61.0GHz,withth of 500MHz,transmit power 10mW and Tx antenna gain 40dBi).As shown in Fig.4, The radar consists of the the RF and IF equipments that changes the stepped frequency signal by 3.5 μ sec intervals, the Signal Processing equipment that perform the Stepped multiple frequency CPC processing shown in Fig.2 in real time.

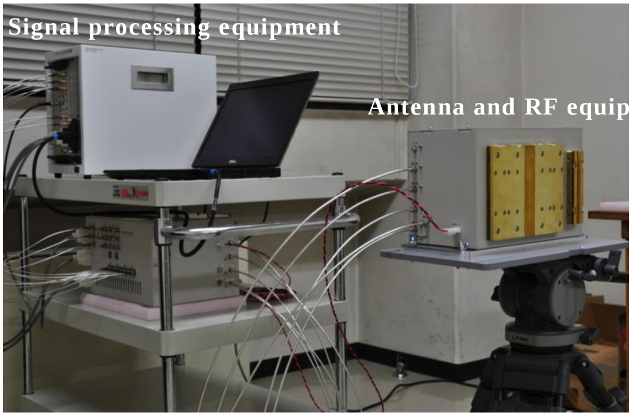

Fig.3 Outline view of the radar

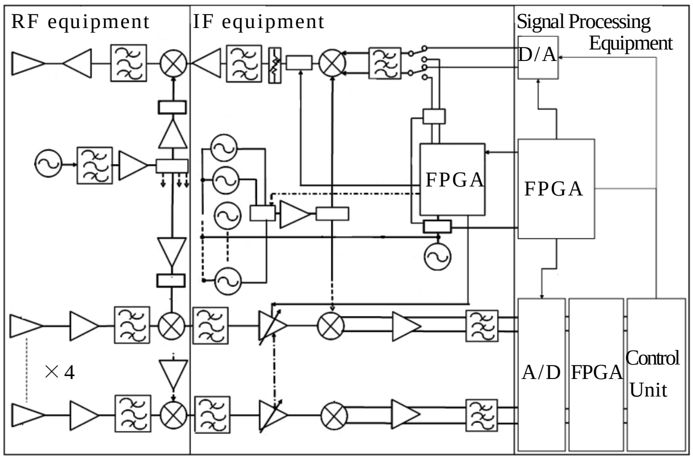

Fig.4 Block diagram of the radar

Table 1 Radar parameter

Transmit frequency	60.25-60.75GHz
Pulse bandwidth	80MHz
Pulse width	0.2 μ sec(30m)
Code length	16
PRI	3.5 μ sec
Pulse number: M	512
Frequency step width	60MHz
Frequency step number: N	8
Transmission bandwidth	500MHz
Observation time	29msec
A/D sampling frequency	160MHz

It is important to note that the radar utilized the 160MHz A/D shown in Table 1 provides the range resolution at 30cm (equivalent to 500MHz bandwidth which is equal to transmission frequency bandwidth）.

The development schedule of the millimeter radar (Experimental model) is shown in Fig.5. The development of the millimeter radar(Experimental model) and an experimental study using 24GHz off-line radar have been completed. Hereafter, the millimeter radar (Experimental model) should be evaluated in the actual automotive and railway traffic environments until the end of FY2011.

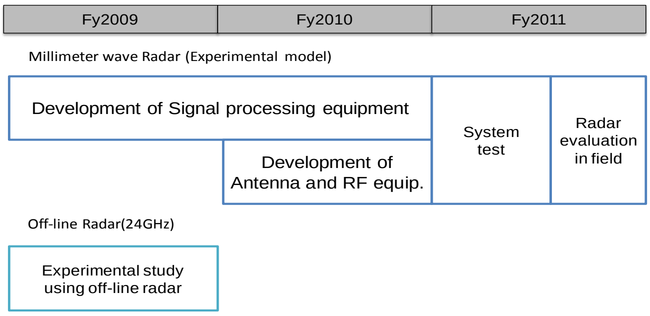

Fig.5 Development process of the radar

3.1. RF and IF equipment

Fig.6 shows the RF equipment that has Tx/Rx Antenna. Fig.7 shows the IF equipment that has the interface with the signal processing equipment. The Tx slot antenna has 22dBi antenna gain in accordance with the specified low power radio station standard (shown in Table 2).The stepped frequency signals from each eight PLL circuits are switched and mixed with CPC signals from D/A of Signal Processing equipment into the IF signal in the IF equipment. The IF signal are up-converted to millimeter wave and amplified in the RF equipment. Namely, the double-conversion architecture is adapted. On the other hand, The reflected millimeter wave signal received with each 4 Rx slot array antenna are amplified and down-converted to baseband signal denoted by Eq(2).

In addition, because the each 8 frequency steps can be set arbitrarily by software, our proposed range sidelobes reduction method in synthetic wideband processing using the nonlinear frequency step can be applied.

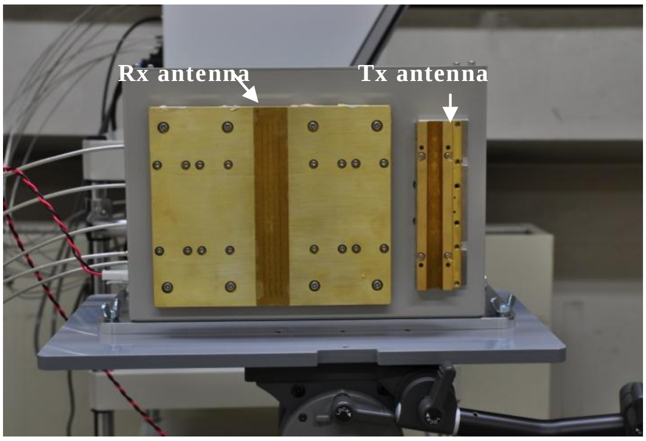

Fig.6 Antenna and RF equipment

Fig.7 IF equipment

Table 2 RF and IF equipment specification

Transmit frequency	60.25GHz～60.75GHz
Switch frequency	8ch
Tx antenna	Slot antenna
Tx antenna gain	22dBi
Rx antenna	Four element slot array antenna
Polarization	Horizontal wave

3.2. Signal processing equipment

As shown in Fig.8, the signal processing equipment consists of the signal processing unit and the control unit. The signal processing unit consists of four compact PCI boards, such as the two of 4 A/D+2FPGA which perform signal processing, the 2D/A+FPGA which generates the CPC signals and control signals and the control unit I/ F board. In the signal processing unit, the baseband signals from 4 Rx antennas are converted into IQ-complex digital signals by 8 A/D converters at 160MHz, 16bit.4 IQ-complex digital signals at 160MHz, 16Bit from Rx antennas are set into Vertex-5 XC5VLX330 FPGAs and processed by the method mentioned in chap2 in real time. In the controller unit, the four signals processed by synthetic wideband processing are formed into five multi-beams, and applied to monopulse angle estimation method. Finally, the estimated relative velocity and high resolution range and angle of targets are indicated by GUI.

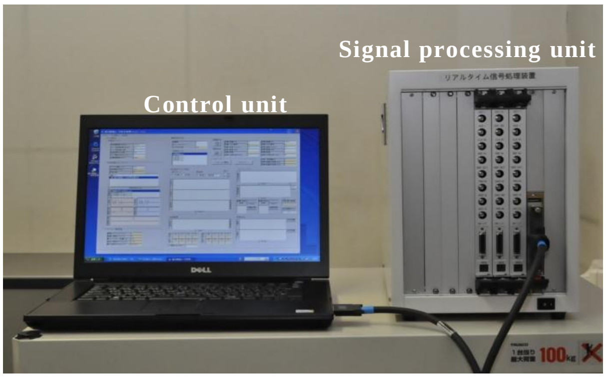

Fig.8 Signal processing equipment

3.3. Experimental study with 24GHz radar

The experimental study using 24GHz radar configured of general measuring instruments such as programmable vector signal generator to evaluate the range resolution of Stepped multiple frequency CPC and to develop the firmware for millimeter radar (experimental model) was performed. The radar parameter for the transmit frequency at 24GHz and the bandwidth of 80MHz was designed, as shown in the table 3 and 4.An experimental measurements in anechoic chamber were carried out radiating the radar signal to the moving target .

Fig.9 Outline view of 24GHz radar

Table 3 Radar parameter in 24GHz radar

Transmit frequency	24.15GHz
Pulse bandwidth	10MHz
Pulse width	1.6μ sec(240m)
Code length	16
PRI	3.25μ sec
Pulse number: M	1024
Frequency step width	8.857MHz
Frequency step number: N	8
Transmission band width	72MHz
Observation time	53msec
A/D sampling frequency	20MHz

Table 4 Expected performance in 24GHz radar

Maximum instrument range	487.5m
Range resolution	2.083m
Velocity field	±215 ㎞/h
Velocity resolution	0.42 ㎞/h

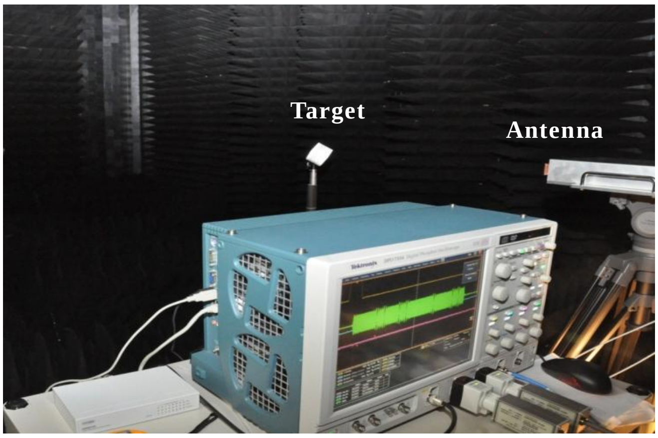

Fig.10 Experimental set up

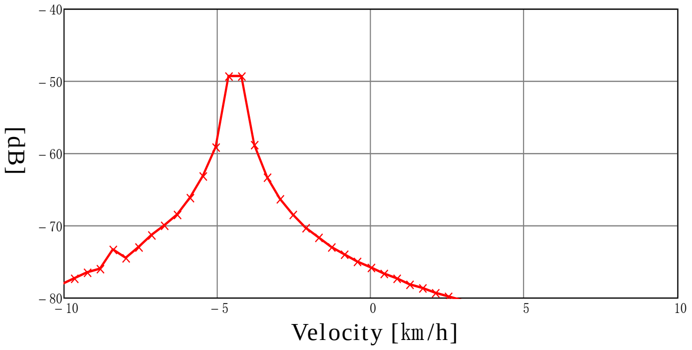

Fig.11 Velocity estimation result

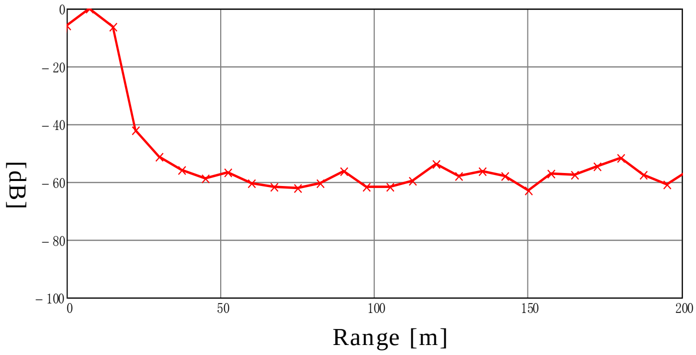

Fig.12 Range estimation result
(Range gate output)

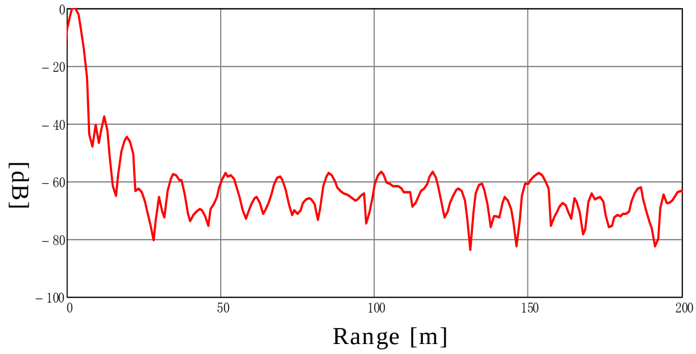

Fig.13 Range estimation result
(Synthetic bandwidth processing output)

Fig.11,12,13 show an experimental result (target range 1.2-2.8m,velocity-4km/h) processed by off-line calculations. In Fig.11,it is shown that an obtained target relative velocity is -4km/h. In Fig.12,the range sidelobes after CPC addition using comparatively short code length of 16 achieves ultra-low level at -60 dB in average between the range from 0 to 200m.The pulse width (in other word, the range gate) after CPC addition is 15m due to the receiver bandwidth of 10MHz. As a consequence, it is confirmed that the range resolution of the expected 2.5m by the synthetic wideband processing was obtained. Table 5 shows the relationship in the ideal range resolution between the 24GHz off-line radar and the millimeter wave radar (experimental model).It is expected that the millimeter wave radar (experimental model) using Stepped multiple frequency CPC modulation provides 30cm range resolution.

Table 5 Comparison of range resolution

Radar	Pulse bandwidth	Range resolution	
		Pulse compression	Stepped multiple frequency CPC
24GHz radar	10MHz	15m	2.5m (experimental value)
Millimeter wave radar	80MHz	2.3m	0.3m (expectation)

4. Conclusion

In this paper, the development of millimeter wave radar using Stepped multiple frequency CPC and off-line experimental result with 24GHz radar in anechoic chamber were presented. Future issue includes to evaluate the millimeter wave radar in an actual field such as railway traffic environment. This study was supported by the Program for Promoting Fundamental Transport Technology Research (No.2009.02) from the Japan Railway Construction, Transport and Technology Agency (JRTT)

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