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Angle Estimation Method using Blocking Matrix in Stepped Multiple Frequency Complementary Phase Code Modulation

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Abstract In this paper, we consider the angle estimation method using monopulse angle estimation in the situation where the targets has same velocity and are located on very close range which is comparable to the range resolution. For these situations, we consider the angle estimation method using combination of Super-Resolution (SR) and Blocking Matrix (BM). From the simulation results, the bias error of the proposed method is less than 0.5 deg from the true value, when the input S/N is enough high. It also shows a tendency that the random error of proposed method is lower than that of conventional method and the error reduced with the increasing S/N ratio. From the initial experimental result, the proposed method can obtain the target angle by monopulse angle estimation for the targets which have same velocity and are located on very close range, which is equivalent to the half of range resolution.

Key words Radar, multiple frequency, Complementary Phase Code, Array antenna, Super-resolution method

1. Introduction

As a part of Intelligent Transport System (ITS), radar has come to draw attention to be utilized for automotive sensors, railway crossing obstacle detectors, pedestrian detectors on crossings and so on, since it can detect targets under following conditions: day and night, backlight and severe weathers. In these applications, radar is required to detect the target in long range and achieve a high range resolution. Frequency Modulation Continuous Wave (FMCW) radar, which provides a high range resolution with less signal processing, is generally employed for current automotive radar. However, the miss-pairing of the detected beat-frequency in the up sweep and the down sweep of FMCW is possible to cause problems under the multiple target situations [1].

Based on the background described above, we have proposed stepped multiple frequency complementary phase code (CPC) radar [2] [3] which employs intra-pulse phase coded by CPC. Adding the pulse compression results using a pair of complementary code trains with compensation of Doppler shift made it possible to achieve the extremely low range side-lobe. In the individual range gate, then the synthetic bandwidth processing, which adopts flourier transform, achieves the high range resolution comparable to the transmission bandwidth. We have previously reported that the expected performance on the sidelobe and the range resolution were demonstrated in experiments [4].

On the other hand, automotive radar also required to estimate the angle of the target to know the target positions to identify the lane where the front vehicle goes. Stepped multiple frequency complementary phase code (CPC) radar employs monopulse angle estimation. Monopulse angle estimation is expected to work for single target situations in principle. Millimeter wave radar using stepped multiple frequency CPC has both a high range resolution and a long-range detection performance. After the Doppler and range estimation with a high resolution, the targets are mostly isolated into one target on a Doppler and range bin. Therefore the monopulse angle estimation can work in the situations. Thus the stepped multiple frequency CPC is considered to match monopulse angle estimation, since monopulse angle estimation can be conducted for each Doppler and range bin [5]. In this paper, we consider the angle estimation method using monopulse angle estimation in the situation where the targets has same velocity and are located on very close range which is comparable to the range resolution. For these situations, we consider the angle estimation method using combination of Super-Resolution (SR) and Blocking Matrix (BM).

2. Methods

2.1 Angle Estimation in Stepped Multiple Frequency CPC using SR and BM

The radar using stepped multiple frequency CPC transmits and receives CPC pulses. As shown in Fig.1, two pulses on the same frequency step are modulated by Code1 and Code2, which satisfies the complementary condition each other. The transmitted carrier frequencies are stepped N times in one sequence and the same sequences are repeated M times. Fig.2 (a) shows the block diagram of signal processing of Stepped Multiple Frequency CPC [3]. As shown in Fig.2 (a), Doppler frequencies, which correspond to the relative velocities of the targets, are estimated by FFT on each range bin of pulse compression result for the same transmitted carrier frequencies. After the ADD processing subsequent to Doppler compensation, then the target ranges for the corresponding velocities are obtained by synthetic wideband waveform.

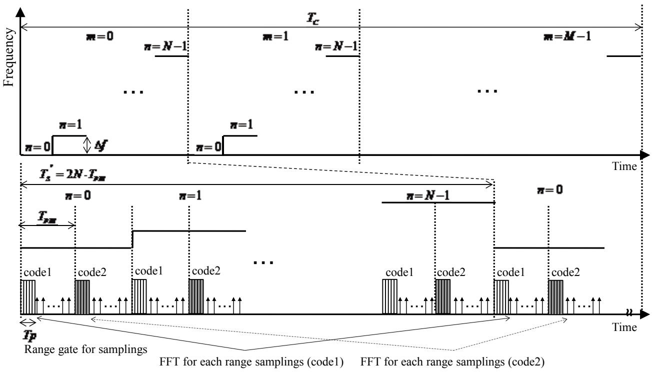


Fig.1 Transmission frequency sequence of stepped multiple frequency CPC

The radar system developed by our research group has 4 receiving antennas. The system adopts DBF (Digital Beam

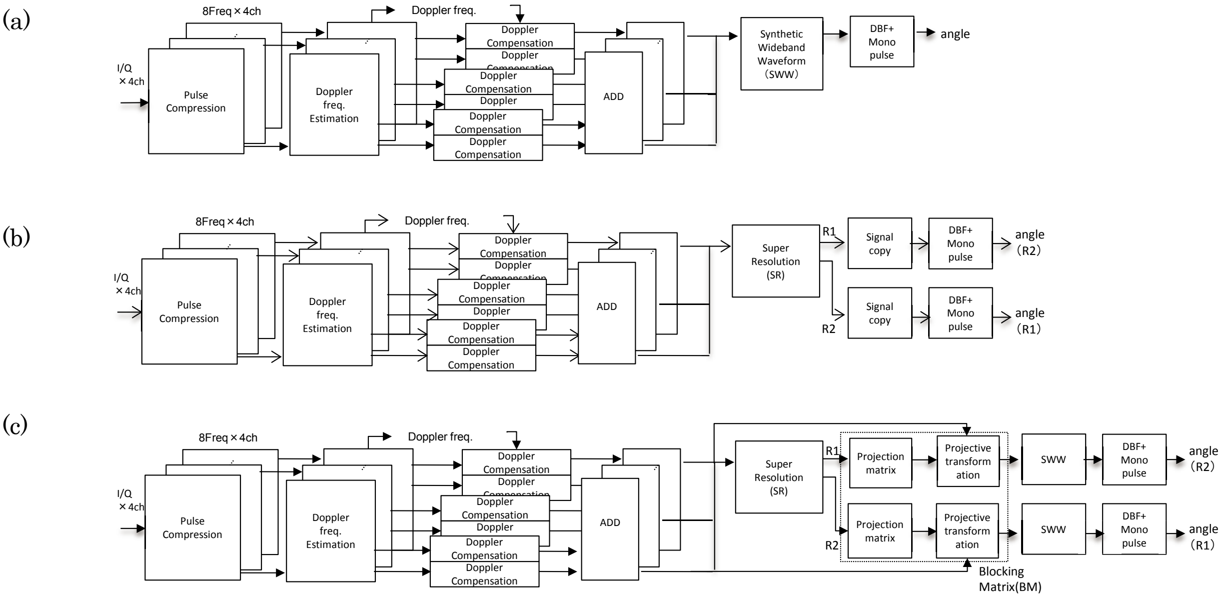


Fig.2 Block diagram of angle estimation in stepped multiple frequency CPC using SR and BM

Forming) and monopulse measurement processing.

To address the situation described in Introduction, where the targets has same velocity and are located on very close range, angle estimation method using SR and BM methods are applied to the stepped multiple frequency CPC. In the situation considered in this paper, the ranges between the targets as well as velocities are very close, thus the condition on the range Doppler bin corresponding to the targets is multiple target situation at the input of angle estimation. In this section, we describe the angle estimation method with monopulse angle using combination of SR and BM method [6] [7]. Stepped Multiple Frequency CPC with angle estimation method using SR and BM method is expected to make it possible to estimate the angle of individual targets which has same velocity and are located on very close range. After the ADD processing, the output at a range bin of s, where the target exist is described as

$$x_{k,s}(l,n)=\sum_{tg}\exp\left[j(-\frac{4\pi\Delta f}{c}R_{tg})\cdot n+j(2\pi\frac{d}{\lambda}\sin(\theta_{tg})\cdot l)\right] \quad (1)$$

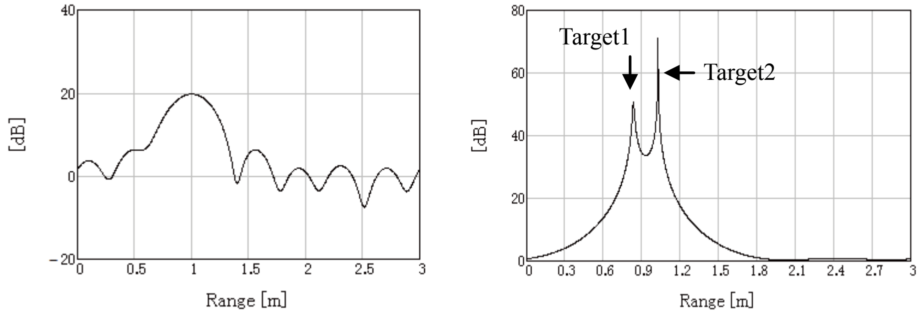
where *k* is the Doppler frequency channel number that is associated with the relative velocity detected by the Doppler frequency estimation processing. Here, the amplitude is 1 for the sake of simplicity. In equation (1), θ is the angle of the target. *c* is speed of light. λ is the wavelength of transmitted signals. Here, Δf is enough small compared to the transmission frequency f_0 , thus the wavelength of transmission at each frequency step is assumed to be $\lambda \equiv \lambda_n = c/f_n (n=0,1,....N-1)$. The index *l* and *n* are correspond to the number of each receiving antenna and the frequency step, respectively.

Fig.2 (c) shows the angle estimation using SR and BM in the Stepped multiple frequency CPC. The steering vector of SR for range estimation is described by $\boldsymbol{a}(r)$. In terms of the orthogonal characteristics of eigenvectors in the signal and noise subspaces, the MUSIC spectrum is given by the equation (2). [8]

$$\boldsymbol{P}_{MU}(r)=\frac{a^H(r)a(r)}{a^H(r)\boldsymbol{E}_N\boldsymbol{E}_N^H a(r)} \quad (2)$$

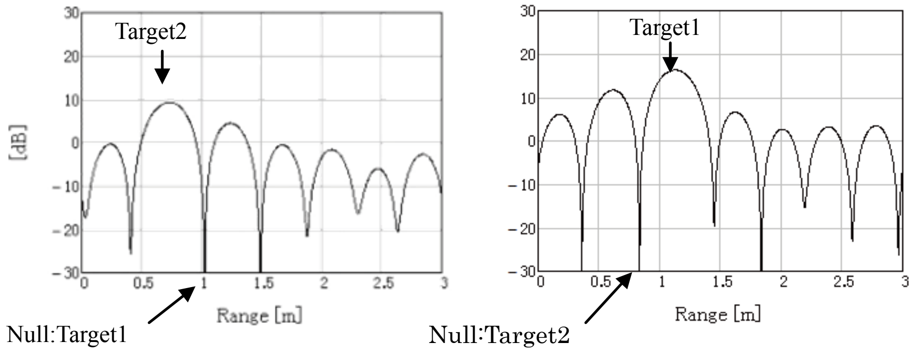
$$\left(\boldsymbol{a}(r)=\exp\left[-j2\pi\left(\frac{2R}{c}\Delta f\right)n\right], \quad \boldsymbol{E}_N=\left[\boldsymbol{e}_{L+1},....,\boldsymbol{e}_K\right]\right)$$

Here, $\boldsymbol{e}_{L+1},....,\boldsymbol{e}_K$ are the eigenvectors belonging to the noise subspace. At first, we estimate the ranges of targets (r_1, r_2) using SR method. The input y_{ch} of the monopulse angle estimation for the targets 1 and 2 using SR method is generally considered to be



(a) SWW for the result of the post ADD (b) MUSIC for the post ADD

Fig.3 Range Estimation result



(a) Target 1 (b)Target2

Fig.4 Result of SWW after adopted BM for each target obtained by signal copy (SC) described by following equation as shown in Fig.2 (b).

$$y_{ch} = \boldsymbol{a}^H(r_1)\boldsymbol{x}_{ch} \quad \text{(for target 1)}$$

$$y_{ch} = \boldsymbol{a}^H(r_2)\boldsymbol{x}_{ch} \quad \text{(for target 2)} \qquad (3)$$

Then we create a projection matrix $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$ to suppress the signal component corresponding to r_1 and r_2, respectively. The output data vector of ADD process of each antenna (ch) $\boldsymbol{x}_{ch}$, is multiplied by P_2 from left, which is called projective transformation in this paper. The input of the monopulse angle estimation is produced by inner product of $\boldsymbol{a}(r_1)$ and $\boldsymbol{P}\boldsymbol{x}_{ch}$. The same process is performed for the target of range r_2.

$$y_{ch} = a^H(r_1)\boldsymbol{P_2}\boldsymbol{x}_{ch} \quad \left(\boldsymbol{P} = \boldsymbol{I} - \frac{\boldsymbol{a}(r_2)\boldsymbol{a}(r_2)^{\boldsymbol{H}}}{\boldsymbol{a}(r_2)^{\boldsymbol{H}}\boldsymbol{a}(r_2)}\right) \quad \text{(for target 1)}$$

$$y_{ch} = a^H(r_2)\boldsymbol{P_1}\boldsymbol{x}_{ch} \quad \left(\boldsymbol{P} = \boldsymbol{I} - \frac{a(r_1)a(r_1)^H}{a(r_1)^H a(r_1)}\right) \quad \text{(for target 2)} \qquad (4)$$

3. Simulation results

The computer simulation uses the following parameters of the stepped multiple frequency CPC radar.

- Transmission frequency: 60.28-60.71GHz
- Pulse repetition interval T_{PRI} : 3.5 us
- Number of frequency steps N : 8
- Step width : 50MHz
- Transmission bandwidth B: 430MHz
- Number of the same frequency step within the observation time M: 512
- Observation time *CPI*: 29ms (velocity resolution δV = 0.3km/h)

Table 2 Target condition in the computer simulation

	Range	Angle	Velocity
Target 1	0.852m	1 deg	3.1km/h
Target 2	1.023m	6 deg	3.1km/h

Fig. 3 shows the result of synthetic wideband waveform processing (SWW) of Stepped multiple frequency complementary phase code (CPC) shown as Fig. 2 (a) and SR method as shown in Fig.2 (b) and (c), where the input S/N for SR is set to be 27dB. From Fig.3 (b), the ranges of two targets 0.85m and 1.02m, respectively are obtained, although SWW cannot isolate. By using the range estimation results, BMs are created for individual ranges.

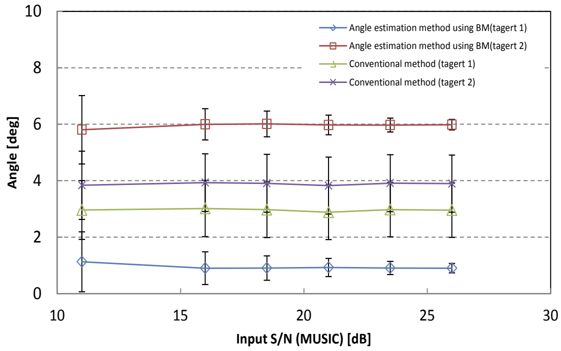


Fig.5 The dependence of angle estimation accuracy on S/N

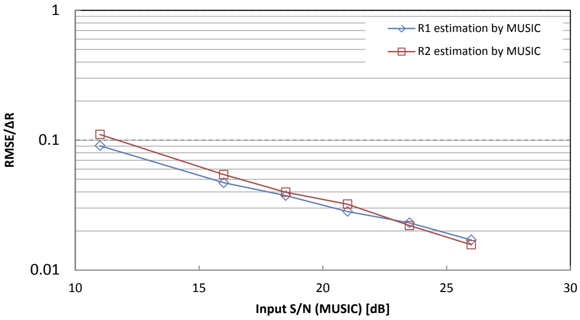


Fig.6 The dependence of RMSE of range estimation by MUSIC on S/N

Fig.4 shows the input of the monopulse angle estimation produced by inner products of $\boldsymbol{a}(r)$ and $\boldsymbol{P_2}\boldsymbol{x}_{ch}$ as well as $\boldsymbol{a}(r)$ and $\boldsymbol{P_1}\boldsymbol{x}_{ch}$. The monopulse angle estimations for targets 1 and 2 produce 1.1 degrees, and 6.4 degrees, respectively. The estimation results using normal signal copy also produce 1.9 degrees, and 2.8 degrees.

As described in previous paragraph, the angle estimation results using combination of SR and BM indicate good agreement with the given target conditions.

The S/N dependence on the angle estimation accuracy is also investigated for two methods and is shown in Fig. 5. Green and blue lines which correspond to the results by SR-SC and SR-BM, respectively indicate the angle estimation results for target 1, which is set to 1 deg. Purple and red lines indicate the angle estimation results by SR-SC and SR-BM for target 2, which is set to 6 deg.

From Fig. 5, the conventional method shows a bias error of about 2deg from the true value regardless of S/N. It is considered that the angle estimation is affected by interference between the target signals. On the other hand, the bias error of the proposed method is less than 0.5 deg from the true value, when the input S/N is enough high. It also shows a tendency that the random error of proposed method is lower than that of conventional method and the error reduced with the increasing S/N ratio.

Fig. 6 indicates S/N dependence on RMSE of target range estimation of the SR. From Fig. 6, the accuracy of range estimation depends on the input S/N. The S/N of 20dB, where RMSE of range estimation is 0.04, corresponds to the random error of 0.5deg.

4. Experimental results

The initial experiment in an anechoic chamber is conducted using same radar parameters as the computer simulation described in section 3. The stepped multiple frequency CPC radar used in the experiment has an array antenna composed of 4 receiving element. Beam width of the four elements by DBF is about 10deg. We use two corner reflectors having 10 dBsm targets for the targets. The target conditions are shown in Table 3. As shown in Fig. 7, two corner reflectors are moved at the same speed of 4km/h with keeping the range difference of 17cm by using an actuator. Fig.8 shows the result of MUSIC. The input S/N of MUSIC is about 36dB on the experiment. From the SR result, we obtain the range of 19.04m and 19.22m for target 1 and 2, respectively.

By using the range estimation results, BMs are created for individual ranges. Figs.9 (a) and (b) shows the input of the monopulse angle estimation for the antenna number 2 (ch=2). These are produced by inner products of $\boldsymbol{a}(r)$ and $\boldsymbol{P_2 x}_{ch}$ as well as $\boldsymbol{a}(r)$ and $\boldsymbol{P_1 x}_{ch}$. From Fig.9 (a) and (b), it can be seen that nulls are formed associated with each target range. Finally, we can obtain 0.6 and -1.6 deg for two targets, respectively.

From the initial experimental result, the proposed method could obtain the target angle by monopulse angle estimation for the targets which have same velocity and are located on very close range, which is equivalent to the half of range resolution.

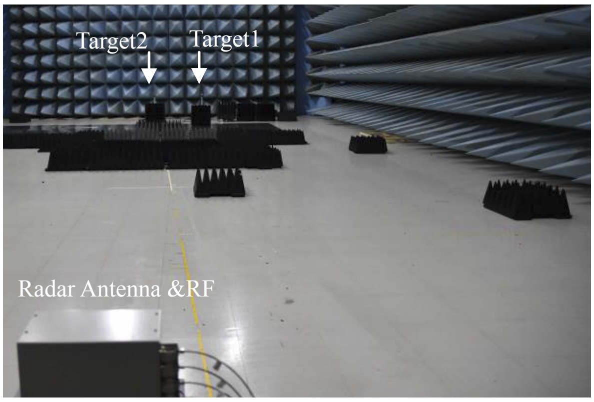


Fig.7 Experimental set up in anechoic chamber

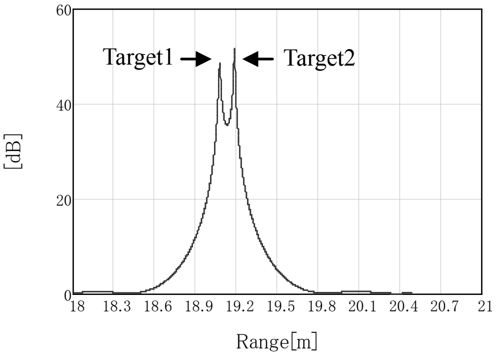
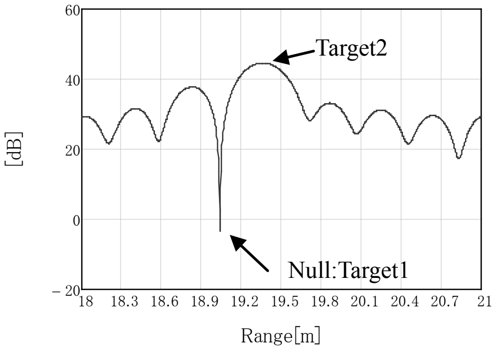
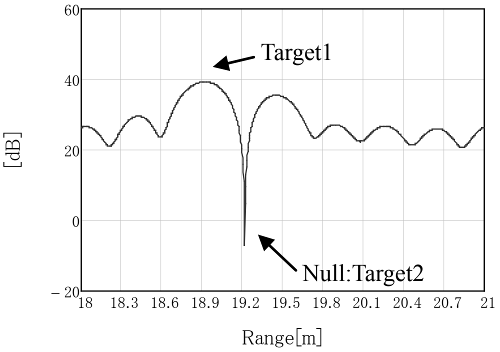


Fig.8 Range Estimation result(MUSIC)



(a)Target1



(b) Target2

Fig.9 Result of SWW after adopted BM for each target

5. Discussion and Summary

In this paper, we consider the angle estimation method using monopulse angle estimation in the situation where the targets has same velocity and are located on very close range which is comparable to the range resolution. For these situations, we consider the angle estimation method using combination of SR and BM.

From the simulation results, the bias error of the proposed method is less than 0.5 deg from the true value, when the input S/N is enough high. It also shows a tendency that the random error of proposed method is lower than that of conventional method and the error reduced with the increasing S/N ratio.

From the initial experimental result, the proposed method can obtain the target angle by monopulse angle estimation for the targets which have same velocity and are located on very close range, which is equivalent to the half of range resolution.

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