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Fundamental Experiments on Super Resolution Range/Angle Estimation by Millimeter Wave Radar using Stepped Multiple Frequency Complementary Phase Code Modulation

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Abstract Millimeter wave radar using stepped multiple frequency Complementary Phase Code (CPC) Modulation has been developing by the research group of the University of Electro-Communications (UEC). In this paper, we proposed the way to utilize the super resolution method such as MUSIC for range/angle estimation using two dimensional receiving signals of the radar. The two dimensional signals consist of complex data obtained at each antenna and each carrier frequency. We also show the fundamental experimental results on the range and angular resolutions of the method in an anechoic chamber and on a field. These results indicate that Stepped Multiple Frequency CPC with 2-D MUSIC works and can estimate range and angle of targets even in the case that they have same Doppler frequency.

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 com
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, radar also required to estimate the angle of the target to know the target positions. Especially in the close range in applications of automotive sensor and pedestrian detector on a street crossing where many targets are possible to exist, a high angular resolution as well as a high range resolution is also required in such situations. In the previous research, method to range/angle estimation method using two dimensional (2-D) MUSIC in Stepped multiple frequency interrupted CW (ICW) with DBF antenna has been proposed and evaluated by simulations [5]. In this paper, we proposed a way to apply the 2-D MUSIC method to the Stepped multiple frequency CPC to estimate range and angle of the targets. We also show the fundamental experimental results conducted in an anechoic chamber and on a field.

2. Methods

2.1 Stepped Multiple Frequency CPC with 2-D MUSIC

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 shows the flowchart of signal processing of Stepped multiple frequency CPC [3]. As shown in Fig.2, Doppler frequencies, which correspond to the relative velocities of the targets, are estimated by FFT on the receiving signals 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 bandwidth processing.

The radar system developed by our research group has 4 receiving antennas. The system adopts DBF (Digital Beam Forming) and mono-pulse measurement processing. The radar system is now upgrading to improve its performance. To improve the range and angular resolution, 2-D MUSIC method using two dimensional receiving signals is applied to the Stepped multiple frequency CPC. In the situation considered in this paper, the angles between the targets as well as ranges are very close, thus high angular resolution is also required. In this section, we describe the range/angle estimation method based on 2-D MUSIC algorism [5]. Stepped multiple frequency CPC with 2-D MUSIC is expected to make it possible to achieve both high range and angular resolutions. That means the method is expected to distinguish the targets existing very close angles and ranges. After the ADD processing, the output at a range bin of s, where the target exist is described as

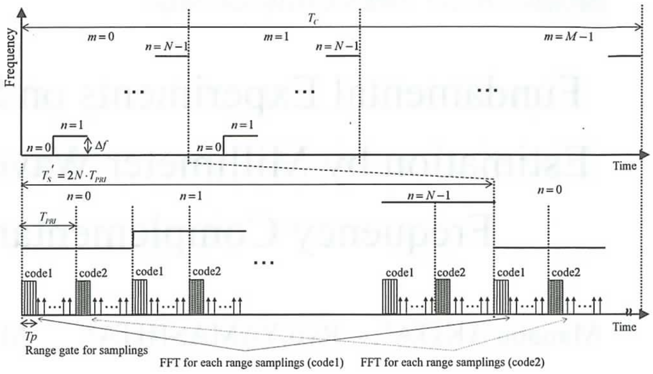

Fig.1 Transmission frequency sequence of stepped multiple frequency CPC

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

where k is the 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

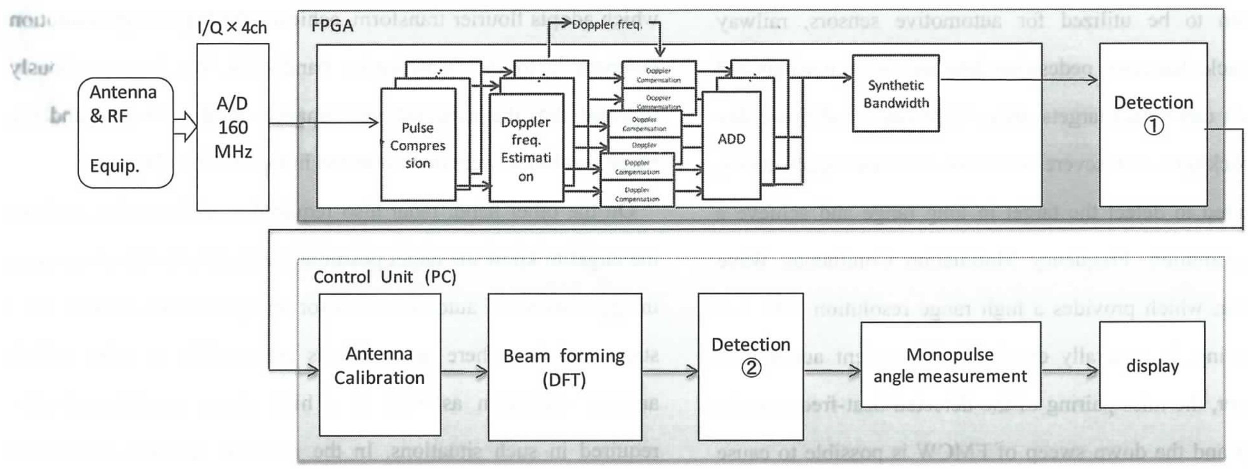

Fig.2 Schematic diagram of Signal processing of Stepped Multiple Frequency CPC radar.

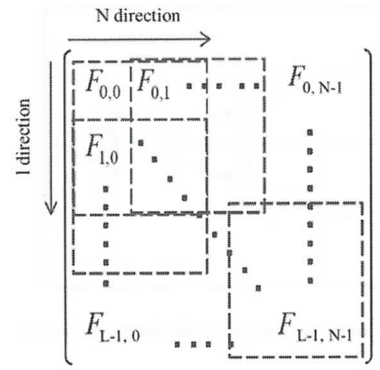

Fig.3 Matrix element of **F** that is composed of linear arrays of l and n directions of observed signal and the extraction of sub-matrix.

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. From the equation (1), the output of ADD processing, θ and R are expected to be obtained from the phase gradients associated with l and n, respectively.

The matrix **F** is composed of linear arrays of l and n directions as shown in Fig. 3. For applying MUSIC algorism to calculate the range/angle in multiple target situations, smoothing processing as the preceding procedure for using a super-resolution method is necessary in order to recover the rank of the correlation matrix. The sub-matrix $\mathbf{F}_{q,p}$ that composed of Nq rows and Np columns of **F** is denoted by

$$\mathbf{F}_{q,p} \equiv submatrix[\mathbf{F}; n = q, q+Nq-1,\ L = p, p+Np-1] \in C^{Nq \times Np}$$

$$(q = 0,1,\cdots,N-Nq),(p = 0,1,...L-Np) \quad . \qquad (2)$$

Then the row vector is generated by rearranging the column vectors as

$$\mathbf{F}vec_{q,p} \equiv \left[\mathbf{F}^{<1>}(q,p)^T \mathbf{F}^{<2>}(q,p)^T ... \mathbf{F}^{<Np>}(q,p)^T\right]^T \in C^{(Nq\cdot Np)\times 1} . \qquad (3)$$

The correlation matrix is obtained by ensemble-averaging sub correlation matrix, which is written by

$$\mathbf{R} \equiv \left\langle \mathbf{F}vec_{q,p}\mathbf{F}vec_{q,p}{}^H \right\rangle \in C^{(N_q\cdot N_p)\times(N_q\cdot N_p)} \; .$$

$$= \frac{1}{(L-Np+1)(N-Nq+1)} \sum_{p=0}^{L-Np} \sum_{q=0}^{N-Nq} \mathbf{F}vec_{q,p}\mathbf{F}vec_{q,p}{}^H \in C^{(N_q\cdot N_p)\times(N_q\cdot N_p)}$$

(4)

The MUSIC spectrum is computed by performing an eigen-analysis on **R**. The noise subspace is given by

$$\mathbf{E} = [\mathbf{e}_1, \mathbf{e}_2, ...\mathbf{e}_{NqNp-S}] , \qquad (5)$$

where S is the number of signals. The number of signals is determined by the eigenvalues of **R**. The dimension of data vector ($Np \times Nq$) must be larger than the number of signals. On the other hand, the size of data vector is desirable to be small in terms of the computation load in the eigenvalue analysis and null search of MUSIC. In this research, we employ 18 for the size of data vector (Np=3, Nq=6). The i th element of steering vector $\mathbf{a}(R,\theta)$ to search the target range/angle is

$$a_i(R,\theta) \equiv \exp(j2\pi(\frac{-2\Delta f}{c}R)(\frac{i-\mathrm{mod}(i,Np)}{Np}) + \frac{d}{\lambda}\sin(\theta)\cdot \mathrm{mod}(i,Np))$$

$$\in C^{(Nq\cdot Np)\times 1} \quad , \qquad (6)$$

where mod(x, y) is an operator calculating a remainder of x/y.

The MUSIC spectrum is also given by the following equation

$$MUSIC(R,\theta) = \frac{\mathbf{a}^H(R,\theta)\mathbf{a}(R,\theta)}{\mathbf{a}^H(R,\theta)\mathbf{E}\mathbf{E}^H\mathbf{a}(R,\theta)} \quad . \qquad (7)$$

3.Evaluation on experimental results

3.1 Experiment in anechoic chamber

The fundamental experiment in an anechoic chamber employs the following factors as the parameter of the Stepped multiple frequency CPC radar which can utilize the transmission frequency sequence shown in Fig. 1.

- Transmission frequency: 60.25-60.75GHz
- Pulse repetition interval T_{PRI} : 3.5 us
- Number of frequency steps N : 8
- Step width : 60MHz
- Transmission bandwidth B: 500MHz
- Number of the same frequency step within the observation time M: 512
- Observation time *CPI*: 29ms (velocity resolution δV = 0.3km/h)

On the other hand, the various target factors when there are two targets are as follows.

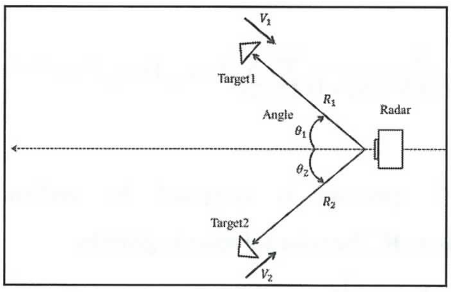

Fig.4 The positional relationship on the experiment in the anechoic chamber.

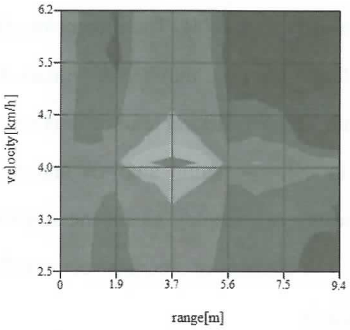

Fig.5 Amplitude of the output of ADD processing (n=0, l=0) on the experiment in the anechoic chamber.

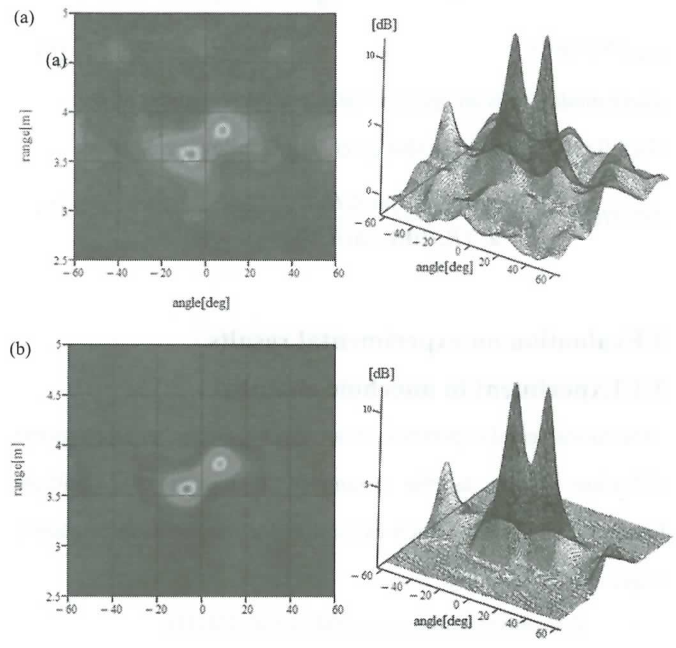

Fig.6 The range/angle estimation result (MUSIC spectrum) in the case of the experiment in the anechoic chamber ((a) 1 snapshot and (b) 4 snapshots).

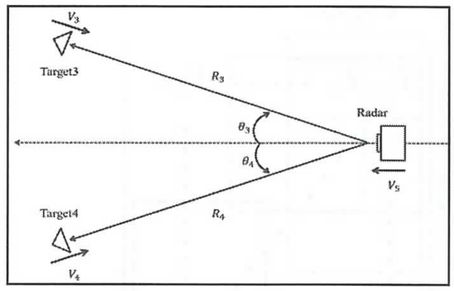

Fig.7 The positional relationship on the field experiment

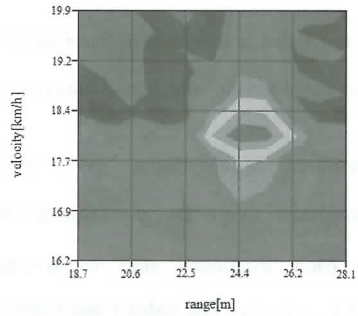

Fig.8 Amplitude of the output of ADD processing

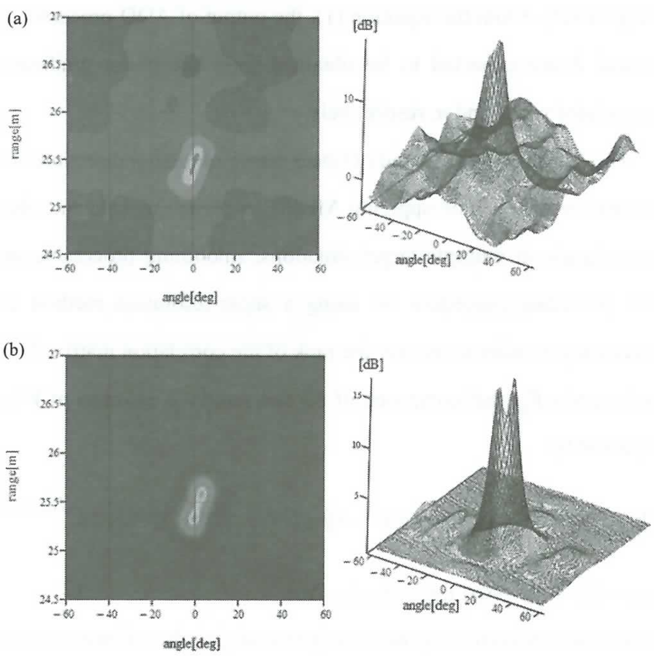

Fig.9 The range/angle estimation result (MUSIC spectrum) in the case of the field experiment. ((a) 1 snapshot and (b) 4 snapshots).

- Number of equal velocity targets within the same range gate: 2
- Target velocities : V_1=V_2=4*km/h*
- Target angles: θ_1=-θ_2=10 *deg*
- RCS of the targets: 10 *dBsm*
- Received power ratio between two targets: 0 dB
- The range difference between targets: R_1-R_2 =0.15m

Fig. 4 shows the positional relationship between targets and the antenna. Fig. 5 shows the amplitude of the output of ADD processing (n=0, l=0). In Fig.5, a peak of amplitude is identified at s=4 and k=13, which correspond to range of 3.6m, velocity of

4.0km/h. Fig.6 (a) shows 2-D MUSIC spectrum using 1 snapshot of 1CPI. In Fig.6 (a), two peaks are identified. One is located at the range of 3.8m and the angle of 7deg, respectively. The other peak is located 3.6m and the angle of -8deg, respectively. These peaks seem to correspond to the two targets as shown in the positional relationship, although the angles of both targets are smaller than the expected values. Fig.6 (b) shows the 2-D MUSIC spectrum using 4 snapshots where the CPI is 7.3ms and the total observation period is equal to the case of 1 snapshot shown above. This result indicates that Stepped multiple frequency CPC with 2-D MUSIC works and can estimate ranges and angles of targets even in the case that they have same Doppler frequency.

3.2 Fundamental Experiment on a Field

The fundamental experiment on a field employs the same factors as in the case with experiment in an anechoic chamber as the parameter of Stepped multiple frequency CPC radar. In the field experiment, radar is equipped on a vehicle front. The target factors are as follows.

- Number of equal velocity targets within the same range gate: 2
- The target velocities : $V_3=V_4=4km/h$
- Received power ratio between two targets: 0dB
- Target angles: θ1=-θ2=5 deg
- RCS of the targets: 10 *dBsm*
- Received power ratio between two targets: 0 dB
- The range difference between targets R_1-R_2 =0.30m
- The velocity of the vehicle: $V_5 \fallingdotseq 20$ *km/h* (by speedometer)

Fig.7 shows the positional relationship on the field experiment. The targets are corner reflectors equipped on actuators. Fig. 8 shows the amplitude of the output of ADD processing (n=0, l=0). In Fig.8, a peak of amplitude is identified at s=27 and k=14 , which correspond to range of 24.6m, velocity of 17.4km/h. Fig.9 (a) shows 2-D MUSIC spectrum using 1 snapshot of 1CPI. In Fig.9 (a), only one broad peak is identified at around the range of 25.5m and the angle of 0 degree. Fig.9 (b) shows the 2-D MUSIC spectrum using 4 snapshots as in the case of Fig. 6(b). In Fig.9 (b), two peaks that cannot be identified in Fig9 (a) can be barely identified.

4. Discussion and Summary

We proposed a method to utilize 2-D MUSIC for range/angle estimation using two dimensional receiving signals of the Stepped multiple frequency CPC radar. The two dimensional signal data consist of the output of Doppler estimation processing at each array and each carrier frequency. We also show the fundamental experimental results on the range and angular resolutions of the method in an anechoic chamber and on a field. These results indicate that Stepped multiple frequency CPC with 2-D MUSIC works both in an anechoic chamber and on a field. The result of experiment in the anechoic chamber indicated that the two targets separated by 15cm in range and 20 degree in angle were distinguished. However, the MUSIC spectrum shown in Fig.6 not so much sharp as that presented by the previous research [5]. One reason for this is considered that the experimental results involve antenna calibration errors. In the real operation, the improvement of the precision of the calibration is required to improve the resolution and accuracy. On the field experimental results, we can identify the difference depending on the number of snap shots.

In this paper, initial experimental results of Stepped multiple frequency CPC with 2-D MUSIC were presented. The decision of the number of signal based on eigenvalue analysis should be also considered as well as the value of Np and Nq for ensemble-averaging the correlation matrix. In the next work, the optimum number of snap shots and the effect of the variation of target range and velocity in the observation period as well as the factors described above should be investigated.

Acknowledgement

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