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Application of DBF in 77GHz Automotive Millimeter-wave Radar

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Abstract. The launch of unmanned models and the introduction of laws and regulations will promote the development of the autopilot industry. The greatest characteristic of millimeter-wave radar is its strong penetration, which can be used in harsh conditions such as rain, snow and heavy fog. It is an indispensable feature for future autopilot. According to the radar band, millimeter-wave radar is divided into 24GHz millimeter-wave radar and 77GHz millimeter-wave radar. 77GHz millimeter-wave radars will be the future development direction due to its farther detection range. Digital Beamforming (DBF) is a new technology that combines the principle of antenna beam forming with digital signal processing technology. At present, DBF is widely used in automotive 77GHz millimeter-wave radar. In this paper, the basic principle of DBF was explained firstly and then the method of amplitude and phase calibration of DBF weight coefficient in engineering was described. Finally the static and dynamic detection effects of automobile millimeter-wave radar based on DBF technology were given.

1. Introduction

In recent years, with the rapid development of artificial intelligence and giving priority to the penetration of the automotive industry, automatic driving has gradually become a strategic industry related to the national automobile industry. Nowadays, lots of researchers working for automotive application have been trying to develop the radar sensors for reducing human casualties from those collision accidents. As the result of this market demand, various radar systems have been widely applied to vehicles[1-3]. Currently, sensors related to automatic driving technology include vision, lidar, millimeter-wave radar and so on. Compared with lidar, millimeter-wave radar not only has all-weather characteristics, but also has a much lower price than lidar. 77GHz millimeter-wave radar has become one of the essential sensors in the automatic driving industry because of its high performance, high integration, small volume and low cost. 77GHz automotive millimeter-wave radar directly obtains the distance information, which is extremely suitable for AEB, ACC and other functions.

In this paper, DBF, one of the key technologies of millimeter wave radar is studied which is the perfect combination of digital technology and antenna technology. DBF is a powerful technique to improve the performance of the radar antenna. 77GHz automotive millimeter-wave radar uses an FMCW waveform as the signal source which is used to obtain the range and velocity simultaneously. The DBF technology is used to detect the azimuth angle[4].

This paper is organized as follows. In Section 2, the basic principle of DBF algorithm are described. In Section 3, an engineering method of calibrating the amplitude and phase of receiving

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antenna for automotive millimeter wave radar is introduced. In Section 4, static and dynamic test results of 77GHz automotive millimeter-wave radar based on DBF technology are given.

2. Basic Principle of DBF

77GHz automotive millimeter-wave radar uses a linear array structure with equal spacing between adjacent array elements. Figure 1 shows a 77GHz automotive millimeter- wave radar antenna array diagram of BOSCH, it has 4 transmit antennas and 8 receiving antennas, each antenna has 16 antenna elements.

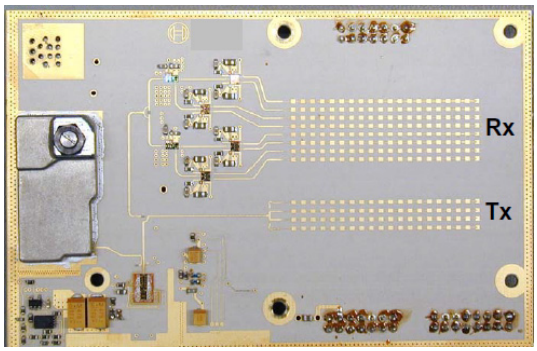


Figure 1. Radar antenna array diagram of BOSCH

The signal sampled simultaneously by M element equidistant linear array is represented by vector $\boldsymbol{X}(t)$, the spacing between adjacent array elements is d, the signal wavelength is λ, and the elements of each array are isotropic. Assume that a target is reflected on the array in the direction of the angle θ to the normal direction of the array as shown in Figure 2.

The spatially propagated signal conforms to Maxwell's wave equation, which is generally a four-dimensional function of space and time[5]. Assume that the target signal at the origin of the coordinate is given by

$$x(0,t) = s(t)\mathrm{e}^{j\omega_0 t} \tag{1}$$

Then the target signal in time t and space position r is given by

$$x(r,t) = s(t - r^T\alpha / c)\mathrm{e}^{j\omega_0(t - r^T\alpha/c)} \tag{2}$$

Where α is the propagation direction vector of the target and c is the propagation velocity of the electromagnetic wave. When The maximum delay of propagating waves across the full array aperture is much less than the reciprocal of the signal bandwidth and the antenna array is a line array, the above four-dimensional function can be defined by

$$x(t) = s(t)\mathrm{e}^{j\omega_0 t} \tag{3}$$

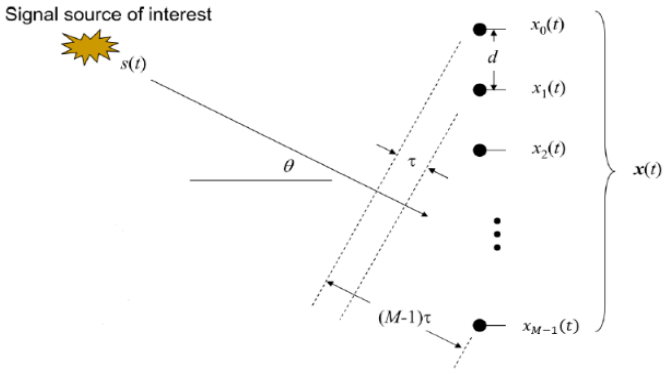


Figure 2. Line array receive target reflection signal

With array element 0 as the reference point, the time for the target to arrive at array element 1 is $\tau = d\sin\theta / c$ later than the time for the target to reach array element 0, the time for the target to arrive at array element 2 is $2\tau = 2d\sin\theta / c$ later than the time for the target to reach array element 0, And so on, the time for the target to arrive at array element M-1 is $(M-1)\tau = (M-1)d\sin\theta / c$ later than the time for the target to reach array element 0. Under the narrowband condition, the array signal is represented by

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \cdots \\ x_M(t) \end{bmatrix} = \begin{bmatrix} s(t)\mathrm{e}^{j\omega_0 t} \\ s(t)\mathrm{e}^{j\omega_0(t-\tau)} \\ \cdots \\ s(t)\mathrm{e}^{j\omega_0[t-(M-1)\tau]} \end{bmatrix} = s(t)\mathrm{e}^{j\omega_0 t}\begin{bmatrix} 1 \\ \mathrm{e}^{j\omega_0\tau} \\ \cdots \\ \mathrm{e}^{-j(M-1)\omega_0\tau} \end{bmatrix} \tag{4}$$

Figure 3 shows DBF is the weighted summation of each array unit signal, that is, using a vector $\boldsymbol{W}$ and array signal $\boldsymbol{X}(t)$ to do an inner product, the weighting coefficients of the M array elements are $\boldsymbol{W}_0$, $\boldsymbol{W}_1$,…,$\boldsymbol{W}_{M-1}$. Weighting coefficient is obtained by

$$W_i = \alpha_i^{-j\Delta\phi_k} \tag{5}$$

Where $\Delta\phi_k = (2\pi / \lambda)d\sin\theta_k$ is array phase compensation value provided, α_i is amplitude weighting required to reduce the side lobe level of a DBF array. After phase and amplitude compensation, the result of adding output signals of each array can be obtained as

$$y(t) = W^H X(t) \tag{6}$$

Where H donates conjugate transpose.

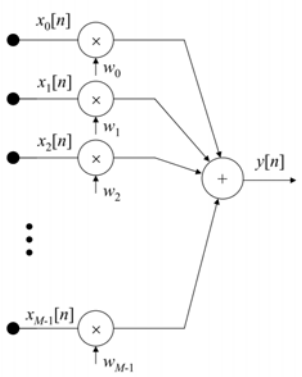


Figure 3. Schematic diagram of digital beamforming

The phases of the complex weight vector $\boldsymbol{W}$ are phase compensated for each component of the array signal so that the respective components are added in-phase in the desired signal direction to form the main lobe of the antenna pattern. In addition, the side lobe of the antenna pattern is added instead of the in-phase signal in other directions, even in individual directions, oppositely-phased signals are added to form the zero point of the antenna pattern[6]. The amplitude of the weight vector $\boldsymbol{W}$ can control the shape of the digital beamforming directional diagram to reduce the side lobe of the pattern. The classic amplitude weight vector is the various window functions in the traditional filter design, such as Taylor, Chebychev, Hamming, and so on. In radar systems, channel inconsistencies often exist, and the channel inconsistency reflects the amplitude and phase inconsistency of the transmission function of the channel, and the method of amplitude phase calibration is needed to solve this problem in engineering. Channel inconsistencies often exist in radar systems, and the channel inconsistency reflects the amplitude and phase inconsistencies of the transmission function of the channel, it is necessary to solve this problem by the method of amplitude and phase calibration.

The specific parameters of the DBF are as follows: the number of antenna array elements is 16, the interval of antenna spacing is 1.9mm, there are 128 wave positions, the angle range of antenna

coverage is ±64 deg, the amplitude weight vector is Taylor window function, and the Taylor distribution parameter is $R = 20\text{dB} / Ne = 5$.

3. Engineering Method of Amplitude and Phase Calibration

DBF has many advantages, such as strong anti-interference ability, easy to realize multi beam and low sidelobe, fast beam scanning, and more flexible control[7]. However, due to the presence of amplitude and phase errors between radar channels, the system performance will be degraded and making it difficult for the DBF to perform well in practical applications. In engineering, the correction of the amplitude and phase errors of the automotive millimeter-wave radar receiving antenna is actually measuring and estimating the inconsistency of the amplitude and phase between the channels as accurately as possible, and then compensating them according to the measured values.

3.1. Amplitude Calibration

When the radar performs amplitude calibration, channel A is used as reference channel, and the radar zero-direction amplitude data of channel B, channel C, and channel D are respectively divided by the radar zero-direction amplitude data of channel A to obtain the amplitude error, the results are shown in Figure 4.

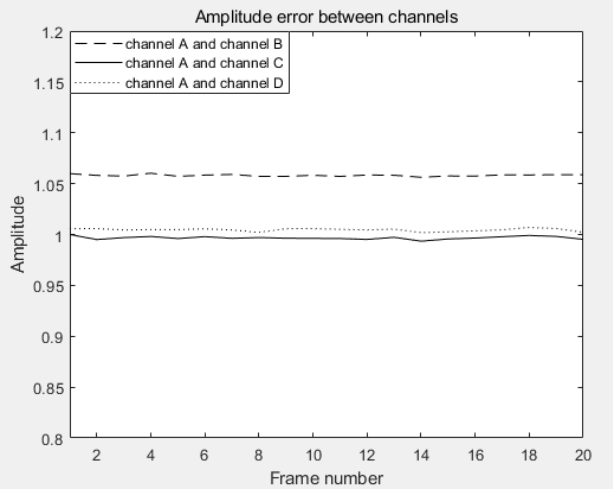


Figure 4. Amplitude error between channels

A total of 20 frames of radar data are used to find the average amplitude error between channels, the results are as follows: the average amplitude error between AB channels is 1.0582, the average amplitude error between AC channels is 0.9969 and the average amplitude error between AD channels is 1.0047. The amplitude calibration is completed by compensating the resulting amplitude error mean to the DBF weight vector $\boldsymbol{W}$.

3.2. Phase Calibration

Radar phase error calibration is mainly divided into phase consistency calibration and antenna phase center compensation. The calibration phase consistency is to modify the effect of phase inconsistency in the signal transmission path, making the same target signal having the same output after four transmission channels. It is necessary to compensate the antenna phase center because the physical center and the phase center of radar actual antenna are very difficult to be same in practice application, there are many factors that can lead to differences, such as errors in the installation of antenna elements, mutual coupling between antenna elements, etc. Calibrating the antenna phase center is also the calibration of radar antenna spacing.

When the radar performs phase calibration, channel A is used as reference channel, the phase difference between channels is obtained by subtracting the phase data of channel A from the phase data of radar channel B, channel C and channel D. The curve of phase difference and angle between

AB channels, AC channels, and AD channels in the -10°, -9°, -8°,…,9°, 10°direction of the radar is fitted to a straight line as shown in Figure 5.

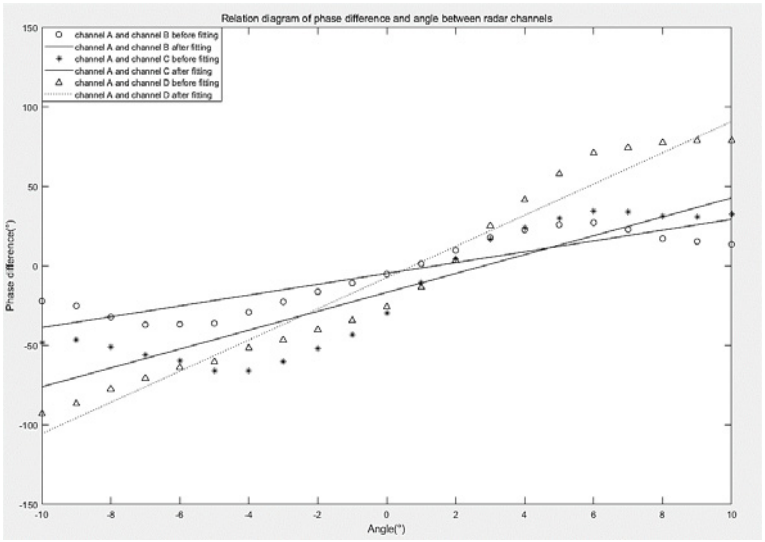


Figure 5. Relation diagram of phase difference and angle between radar channels

The intercept of the straight line is the phase consistency error, and the slope of the straight line is the change rate of the phase difference between channels with the change of the angle. Table 1 shows the consistency error and phase difference change rate between radar AB channels, AC channels and AD channels. The change rate of phase difference is obtained by

$$\frac{d\phi_k}{d\theta_k} = \frac{2\pi}{\lambda} d\cos\theta_k \tag{7}$$

Where ϕ_k is the phase difference between channels, is the angle between the target and the normal direction of the array, is the signal wavelength (77GHZ millimeter wave radar wavelength is about 3.98mm), d is the antenna spacing. In particular, the maximum value of θ_k is 10°, $\cos\theta_k \approx 0.98$ can be ignored, the rate of phase difference is approximately considered as a linear relationship with the antenna spacing d through linear fitting method, and the equivalent antenna spacing of radar can be calculated. The compensation value of antenna spacing is obtained by subtracting the equivalent antenna spacing value from the theoretical design antenna spacing design value (77GHz automotive millimeter-wave radar antenna spacing design value is about 1.9mm). The phase calibration is completed by compensating the phase conformance error and antenna spacing compensation value to the DBF weight vector $\boldsymbol{W}$.

Table 1 Results of Phase Analysis between Radar Channels

Channels	Phase Consistency Error /°	Change Rate of Phase Difference
AB Channels	-114.9	3.41
AC Channels	-36.8	5.94
AD Channels	-87.5	9.81

4. Test Results

4.1. Static Test

A relatively empty space is selected and the radar is fixed to a certain height (about 0.5m) from the ground with a three foot frame. The corner reflector is placed in the position of 20m in the normal direction of the radar as shown in Figure 6.



Figure 6. Radar static test scene

Through the upper computer, the angle information of the target at 20 meters is observed after the radar data has been processed by the upper computer, the target angle information before amplitude and phase calibration as shown in Figure 7, the target angle information after amplitude and phase calibration as shown in Figure 8. The left-to-right information of the target list is the distance of the target, the target speed, the angle of the target, and the Signal Noise Ratio (SNR) of the target, where the SNR data is not read.

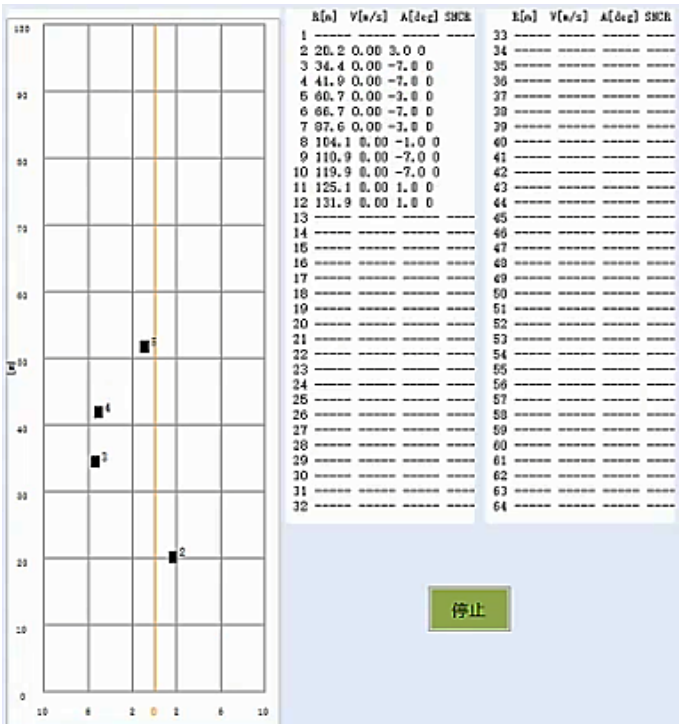


Figure 7. Radar static test results before amplitude phase calibration

Before the amplitude-phase calibration, the detection angle of the target placed in the position of 20m in the normal direction of the radar is 3°(No.2 target in Figure 7); After the amplitude-phase calibration, the detection angle of the target placed in the position of 20m in the normal direction of the radar is 0°(No.3 target in Figure 8). Therefore, amplitude-phase calibration plays an important role in improving the accuracy of the target angle detection of the 77GHz automotive millimeter-wave radar in the DBF system.

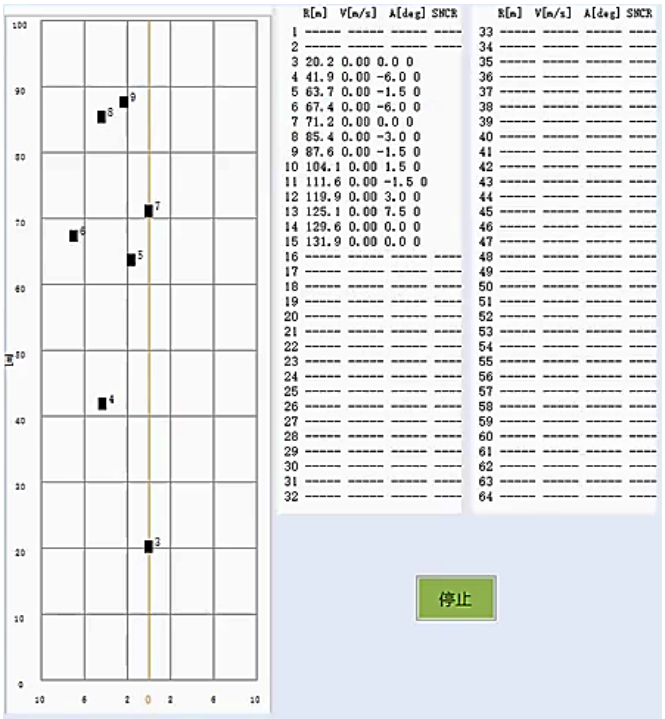


Figure 8. Radar static test results after amplitude phase calibration

4.2. Dynamic Test

77GHz automotive millimeter-wave radar is mainly used to detect forward targets to achieve ACC, AEB and other functions, 77GHz automotive millimeter-wave radar is generally installed in the front of the car as shown in Figure 9. When installing the radar, it is necessary to keep parallel with the ground plane as much as possible, so as to prevent the radar from facing toward the sky or toward the ground, resulting in the inability to work properly.

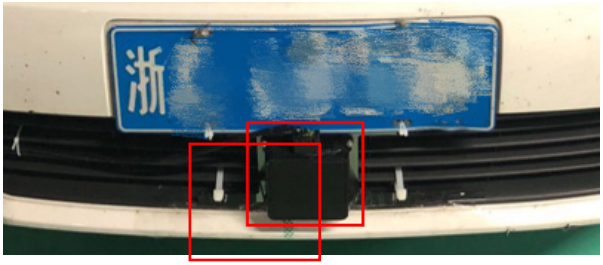


Figure 9. Photograph of 77GHz Automobile Millimeter Wave Radar installation

The measured radar performance on the road is shown in Figure 10. The 77GHz automotive millimeter-wave radar based on the DBF system can more accurately distinguish vehicles or targets in different lanes ahead. In this figure, the red squares indicate that the target, which relative to the speed of the driving car is less than 0m/s, is mainly the surrounding poles and walls. The black squares indicate that the target, which relative to the speed of the driving car is greater than 0m/s, is mainly vehicles. Since the SNR decreases with distance, the accuracy of the angular measurement of a 77GHz automotive millimeter-wave radar based on the DBF system for a target with a distance of more than 120m is significantly reduced.

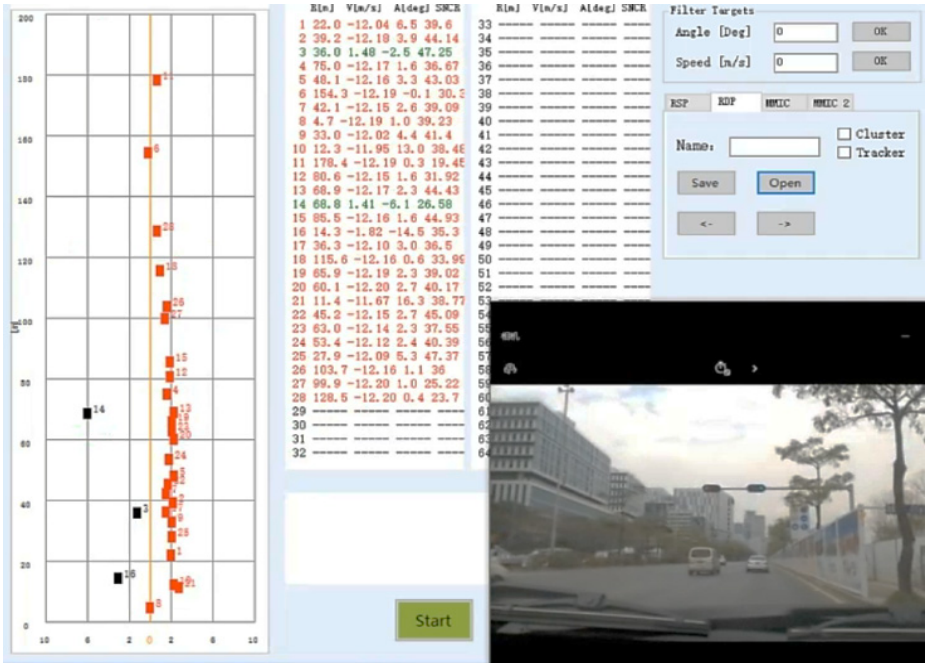


Figure 10. Radar dynamic test results

5. Conclusion

The 77GHz automotive millimeter-wave radar is an important sensor in the autopilot system. It is mainly used to implement safe vehicle distance warning, adaptive cruise control, and automatic emergency braking. This paper mainly introduces the basic principle of DBF, and the engineering method of the magnitude and phase calibration of weight vector W. 77GHz automotive millimeter-wave radar based on DBF system has been widely used, However, the 77GHz automotive millimeter-wave radar of the DBF system is difficult to satisfy the resolution and detection capabilities of the automatic driving, and it is necessary to use a MIMO (multiple input, multiple output) radar algorithm. The good and consistent radar amplitude and phase characteristics are also the basis for realizing the MIMO algorithm.

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