A Method for Precise Distance and Velocity Measurement of Automotive Radar

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Abstract. When using Fast Fourier Transform (FFT) to perform spectrum analysis on frequency modulated continuous wave (FMCW) radar signals, there are problems of barrier effect and spectral leakage. In order to keep away from barrier effect and improve precision of frequency estimation, we propose a method that apply the quadratic function method (QFM) to radar signal processing. The method quickly locates the maximum position of the spectral amplitude by the quadratic curve. The results of simulation and real data processing show that the method effectively solves the problem of the step effect of the distance and velocity estimation under the premise of only requiring adding a small amount of computations.

Keywords: FMCW, FFT, quadratic function method, distance and velocity accuracy.

1. Introduction

As a key component of intelligent driving system, automotive assistting driving radar has been greatly developed and applied in recent years. Distance, velocity and angle are the three major elements of automotive assistting driving radar. In order to achieve high-resolution of distance and velocity, the 2-dimensional Fast Fourier Transform (FFT) method is generally used for frequency modulated continuous wave. However, due to the limit of cost, the radar signal processor can not meet the demand of large-point FFT. It brings serious barrier effect and spectral leakage. Even worse, the distance and velocity unit gap is too large to bring inconvenience to the later data processing.

Many effective methods have been developed to sovle this problem. Rife D C [1-2] uses the point-by-point interpolation of the maximum and the secondary maximum in the main lobe of the signal spectrum to obtain an estimated frequency. Xinyang Li and Hongyuan Wang [3] adopte the method of obtaining the rough range of the peak frequency of the frequency modulated continuous wave (FMCW) radar beat frequency signal by using FFT. And high-precision estimation of frequency is realized by performing spectrum refinement within the range. Junrong Xu and Shenglin Yu [4] study the echo power spectrum and propose to calculate the maximum position deviation using the 3-point value on the side of the peak. Panwei Hou [5] and Lu Yang propose a algorithm combining energy center of gravity method with truncation length adjustment. The energy center of gravity method uses the points in the main lobe of the power spectrum to estimate the position of the center of the main lobe, thus solving the phenomenon of the grid. Bao Liu and Junmin Liu [6] propose a new algorithm to improve the accuracy of distance by combining FFT and Chirp z.

In order to solve the problem that the distance and velocity unit gap is too large, we analyze the characteristic of the radar signal spectrum. We propose to apply the quadratic function method (QFM) to frequency estimation based on spectrum characteristic. The QFM assumes the maximum and the secondary values of the left and right of the spectrum are located on the quadratic curve. Therefore, the position of the maximum value can be obtained by the quadratic curve.

FMCW radar signal processing method by performing 2- dimensional FFT is described in Section II. The QFM is introduced and the error formula is derived by using QFM to estimate frequency value in Section III. In Section IV, the experiments and results are given. Finally, the conclusion is summarized in Section V.

2. FMCW Radar Signal Process

When using the 2-dimensional FFT signal processing method, the FMCW radar needs to transmit the chirp sequence waveform [7]. The chirp sequence waveform consists of L chirp signals. The sweep initial frequency of the chirp signal is f0, the sweep bandwidth is B, and the repetition period is Tchirp. The transmitting waveform and receiving waveform of the chirp sequence are shown in Fig. 1.

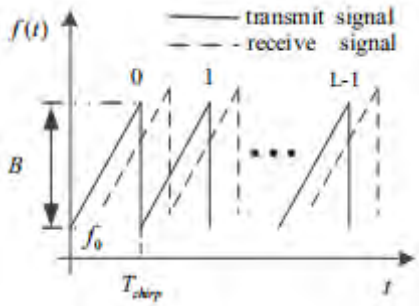


Fig. 1 The transmitting and receiving signal of the chirp sequence

After receiving the echo signal reflected by the target, the FMCW radar directly mixes the echo signal with the transmitting signal to obtain zero-IF signal. The l+1 beat frequency signal is sampled and can be expressed as:

$$s(n,l) = A\exp\left(j2\pi\left(f_b\frac{T_{chirp}}{N}n - f_d T_{chirp} l + \frac{2f_0 R_0}{c}\right)\right) + w(n,l) \tag{1}$$

where A is the signal amplitude, fb is the beat frequency, N is the number of sampling points in one cycle of the chirp sequence, fd is the Doppler frequency, c is the velocity of light, $R0$ is the target distance, $w(n,l)$ is the sampling noise. The beat frequency and Doppler frequency [8] are expressed as follows:

$$f_b = \frac{B}{T_{chirp}}\frac{2R_0}{c} + \frac{2f_0 v}{c}$$
$$f_d = -\frac{2f_0 v}{c} \tag{2}$$

where v is the relative velocity of the target and the radar.

The schematic diagram of the chirp sequences signal processing [9] is shown in Fig. 2:

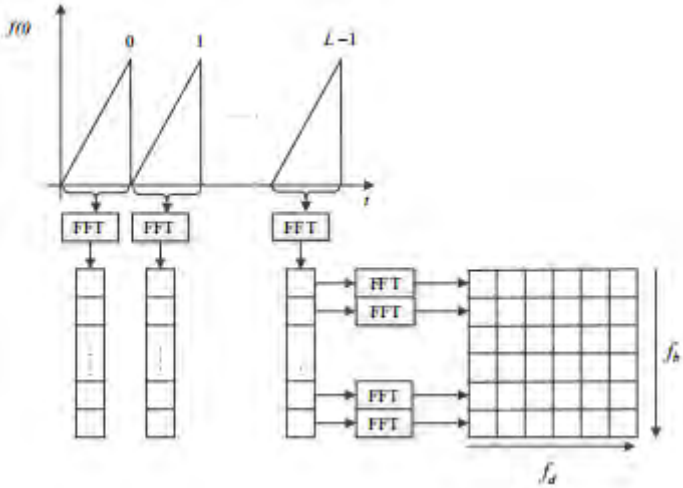


Fig. 2 The schematic diagram of signal processing

The received L echo sequences are divided into 2-dimensional arrays. Each row represents a distance unit and each column represents a velocity unit. When processing the signal, FFT is performed in the signal of each velocity unit firstly, and then the same processing is done for each distance unit. After completing the 2-dimensional FFT, the beat frequency and Doppler frequency can

be calculated according to the position of the maximum in the 2-dimensional spectrum. The beat frequency and Doppler frequency can be expressed as follows:

$$f_b = \frac{k_r}{N_{fftn}} f_s$$
$$f_d = \frac{k_v}{T_{chirp} \times V_{fftn}} \tag{3}$$

where fs is the distance sampling rate, $Nfftn$ is the FFT points for distance, kr is the position of the maximum spectrum for distance, $Vfftn$ is FFT points for velocity, kv is the position of the maximum spectrum for velocity.

The distance and velocity of the target can be calculated according to (4) after obtaining the beat frequency and the Doppler frequency:

$$R_0 = (f_d + f_b)\frac{cT_{chirp}}{2B}$$
$$v = -\frac{f_d c}{2 f_0}. \tag{4}$$

3. Application Of QFM

Due to the "step effect" of the distance and velocity measured by automotive radar, it is difficult to process data in the later step. Therefore, we propose to apply QFM to frequency estimation to improve the accuracy of estimation.

The QFM is based on the maximum and the secondary values of the left and right of the spectrum [10]. The implementation is shown in Fig. 3.

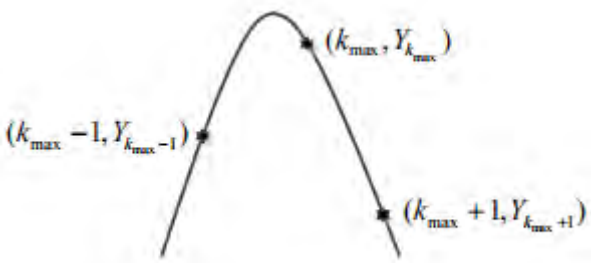


Fig. 3 Illustration of QFM

In Fig. 3, $kmax$ is the coordinate of maximum point acquired after FFT, $Ykmax$ is the corresponding peak value. $kmax$-1 and $kmax$+1 are the coordinates of the two points around the maximum, $Ykmax$-1 and $Ykmax$+1 are the corresponding peaks.

The QFM assumes the maximum value of the spectrum and the left and right times are three points on the quadratic curve. The quadratic curve can be given as:

$$y = ax^2 + bx + c. \tag{5}$$

The position maximum point on the quadratic curve can be expressed as follows:

$$x_{max} = -b / 2a. \tag{6}$$

In order to obtain the coordinate of the maximum point of the curve, the parameters a, b are required. The parameters of the three points are brought into the quadratic curve formula to obtain the coordinate. Since the three points have a fixed positional relationship, we can set the coordinates of the three points to [-1, 0, 1] without affecting the result. The coordinate of the maximum value is as follows:

$$x_{\max} = -\frac{b}{2a} = -\frac{1}{2}\frac{Y_{k_{\max}+1} - Y_{k_{\max}-1}}{Y_{k_{\max}-1} + Y_{k_{\max}+1} - 2Y_{k_{\max}}}. \tag{7}$$

It is necessary to explain the problem that the QFM is applicable to one-dimensional data while the radar signal processing is based on 2-dimensional FFT.

The radar echo signal amplitude after performing 2-dimensional FFT can be expressed as (8).

$$S_f(k_r, k_v) = A' \sin c\left[\frac{N}{N_{fftn}}(k_r + \Delta k_r)\right] \times \sin c\left[\frac{L}{V_{fftn}}(k_v + \Delta k_v)\right] \tag{8}$$

where A' is the theoretical maximum amplitude of the two dimensional spectrum, kr is the beat frequency unit, kv is the Doppler frequency unit, kr= -$Nfftn$/2,...0,...$Nfftn$/2-1, kv=- $Vfftn$/2,...0,...$Vfftn$ /2-1 ; Δkr is the difference between the position of the actual frequency of the beat frequency and th e maximum value of the sampling point, Δkv is the difference between the position of the Doppler actual frequency and the maximum value of the sampling point; Δkr, Δkv ϵ [-0.5,0.5].

$$\sin c(x) = \frac{\sin(\pi x)}{\pi x}. \tag{9}$$

Taking the distance as an example, when QFM is used to estimate the position of the maximum, the maximum value and the secondary values of the left and right are taken out in the velocity unit where the spectrum maximum is located. The three points can be expressed as follows:

$$\begin{cases} Y_{k_{\max}-1} = A' \sin c\left[\frac{N}{N_{fftn}}(\Delta k_r - 1)\right] \sin c\left(\frac{L}{V_{fftn}} \times \Delta k_v\right) \\ Y_{k_{\max}} = A' \sin c\left(\frac{N}{N_{fftn}} \times \Delta k_r\right) \sin c\left(\frac{L}{V_{fftn}} \times \Delta k_v\right) \\ Y_{k_{\max}+1} = A' \sin c\left[\frac{N}{N_{fftn}}(\Delta k_r + 1)\right] \sin c\left(\frac{L}{V_{fftn}} \times \Delta k_v\right). \end{cases} \tag{10}$$

Since the maximum position does not affect the estimation, the maximum position of the 2-dimensional spectrum can be set to (0,0) when calculating the positional deviation of frequency. The maximum coordinate can be obtained by bringing the maximum value and the secondary values of the left and right into (7). The maximum coordinateis are as follows:

$$\begin{aligned} x_{\max} &= -\frac{1}{2}\frac{Y_{k_{\max}+1} - Y_{k_{\max}-1}}{Y_{k_{\max}-1} + Y_{k_{\max}+1} - 2Y_{k_{\max}}} \\ &= -\frac{1}{2}\frac{\sin c[u(\Delta k_r + 1)] - \sin c[u(\Delta k_r - 1)]}{\sin c[u(\Delta k_r - 1)] + \sin c[u(\Delta k_r + 1)] - 2\sin c(u \times \Delta k_r)} \end{aligned} \tag{11}$$

where u=$N/Nfftn$. It can be seen that the Doppler dimension and beat dimension can be processed separately using QFM. It has no effect on the results.

The position of maximum value which is estimated by QFM is the compensated offset of frequency position. The estimated frequency by compensated can be given as follows:

$$\begin{aligned} f_{best} &= (k_{\max} + x_{\max}) \times \frac{f_s}{N_{fftn}} \\ &= \left(k_{\max} - \frac{1}{2}\frac{Y_{k_{\max}-1} + Y_{k_{\max}+1} - 2Y_{k_{\max}}}{Y_{k_{\max}+1} - Y_{k_{\max}-1}}\right) \times \frac{f_s}{N_{fftn}} \end{aligned} \tag{12}$$

The actual frequency of the beat frequency [11] is as follows:

$$f_{breal} = (\Delta k_r + k_{max}) \times f_s / N_{ffin} \tag{13}$$

The error between the estimated frequency and the actual frequency can be expressed as follows:

$$\begin{aligned} \Delta f_b &= f_{best} - f_{breal} \\ &= \Delta k_r \times \frac{f_s}{N_{ffin}} - \frac{f_s}{N_{ffin}} \times \\ &\frac{1}{2} \frac{\sin c[u(\Delta k_r + 1)] - \sin c[u(\Delta k_r - 1)]}{\sin c[u(\Delta k_r - 1)] + \sin c[u(\Delta k_r + 1)] - 2\sin c(u \times \Delta k_r)} \end{aligned} \tag{14}$$

By taking the frequency error into (2), the difference between the actual distance and velocity and the distance and velocity which is obtained by QFM can be solved as (15):

$$\begin{aligned} \Delta v &= -\frac{\Delta f_d c}{2 f_0} \\ \Delta R &= \frac{(\Delta f_d + \Delta f_b)}{2B} c T_{chirp} \end{aligned} \tag{15}$$

where Δfd is the difference between the frequency which is obtained by QFM in the velocity frequency domain and actual frequency, Δfb is the difference between the frequency which is obtained by QFM in the distance frequency domain and the actual frequency.

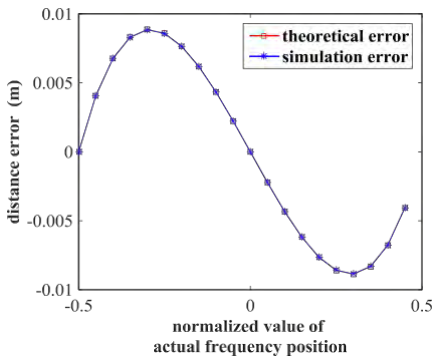
4. Simulation and Real Data Processing

In order to verify the performance of the improved method, the simulation is analyzed firstly. The simulation parameters are set as shown in Table 1.

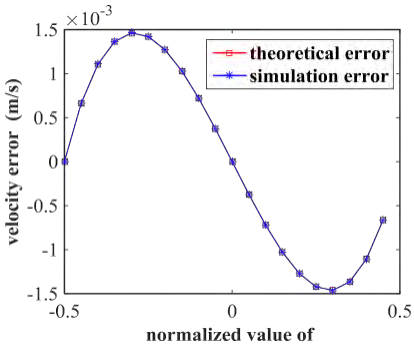
Table 1 The Simulation Parameters

Parameter Name	Parameter Value
Carrier Frequency	24.06GHz
Bandwidth	120MHz
Repeat Frequency	10KHz
Number of Sequences	64
Distance Sampling Points	90
Distance, Velocity FFT Points	256
Distance Resolution Unit	0.732m
Velocity Resolution Unit	0.2438m/s
Velocity Step Interval	0.05*Δvm/s
Distance Step Interval	0.05*Δrm

According to signal processing flow of the FMCW radar and the distance and velocity error obtained by QFM, the theoretical error of velocity and distance and the simulation error can be obtained. The experimental results are shown in Fig. 4.



(a) Distance error



(b) Velocity error

Fig. 4 The theoretical error and simulation error by using QFM

In Fig. 4, it can be observed that the absolute value of the distance error obtained by QFM is less than 0.01m. The distance resolution unit is 0.732m, so the distance error is within 2% relative to the distance resolution unit. The absolute value of the velocity error obtained by QFM is less than 0.0015m/s for velocity. The velocity resolution unit is 0.2438m/s, so the velocity error is within 1% relative to the velocity resolution unit. The theoretical error is basically equal to the simulation error, which illustrates the correctness of the theoretical derivation.

In order to further verify the improved method, the outfield experiment is carried out using the automotive assisted driving radar. The radar is placed at fixed angle and the automobile is moving in the center of the lane. The radar parameters are consistent with the simulation parameters. The schematic diagram of the outfield experimental scene is shown in Fig. 5.

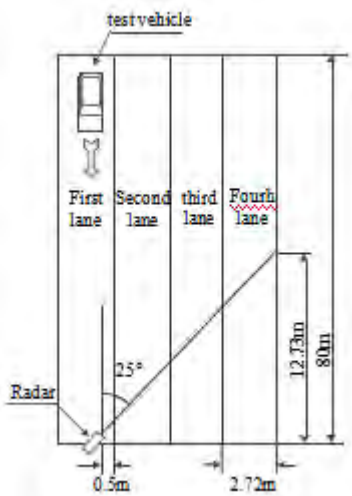
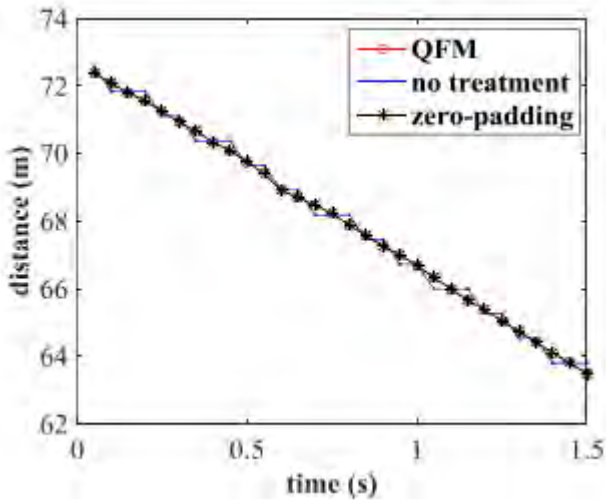


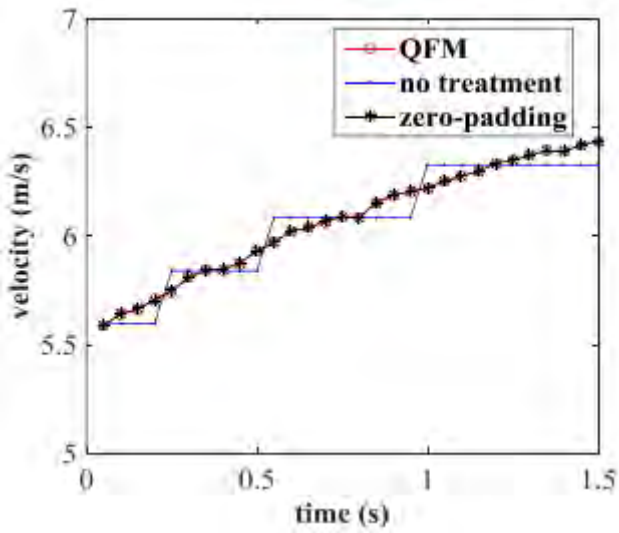
Fig. 5 The outfield experiment scene

Outfield experiments are carried out on the four lanes. The original echo data of the radar are collected and saved. The data are analyzed to verify the improved performance by QFM compared to original function. Since we can not obtain accurate distance from the automobile to the radar and the velocity of the automobile in the actual environment, the distance and velocity obtained by the

zero-padding method to FFT are used as reference values. The zero-padding multiple is 32. When the automobile is in the first lane, result without additional processing, result with QFM process and result with zero-padding process are shown in Fig. 6.



(a) Distance



(b) Velocity

Fig. 6 The outfield experiment result

In order to intuitively observe the difference between result with QFM process and result with zero-padding process, the data of the four lanes are processed by two methods. Meanwhile, the difference between the two results is calculated. The mean value and root mean square of the difference are as shown in Table 2.

Table 2 Difference between the Two Results

Lane	Distance Error		Velocity Error	
	Mean (m)	Root Mean Square(m)	Mean (m/s)	Root Mean Square(m/s)
First	0.0007	0.0094	-0.0003	0.0030
Second	-0.0003	0.0095	0.0002	0.0030
Third	0.0018	0.0149	0.0008	0.0038
Fourth	0.0015	0.0128	0.0002	0.0040

As is shown in Table 2, the distance and velocity measured by the two methods are the same and the mean value of error between results are approximately 0. The root mean square of the distance error is below 0.02m and the root mean square of the velocity error is below 0.005m/s.

The calculation of the two methods is compared in Table 3. Maximum position of the spectrum is estimated using QFM by taking the maximum value and the secondary values of the left and right. It is

independent of FFT points. The estimation of the distance and velocity needs to add 6 times complex multiplication and 6 times complex addition. The additional calculation required for zero-padding method in time domain is increasing rapidly along with the increase of the zero-padding multiple.

Table 3 The Comparison of Calculations

Calculation	QFM	Zero-padding
Multiplication	$\frac{1}{2} MN \log_2 (MN) + 6$	$MN \log_2 (MN) + 6$
Addition	$512MN \times \lceil \log_2 (MN) + 10 \rceil$	$1024MN \times \lceil \log_2 (MN) + 10 \rceil$

Based on Table 2 and Table 3, the calculation with QFM processing is much smaller than the calculation with zero-padding method on the premise that the results are basically the same.

5. Conclusion

In this paper, the 2-dimensional FFT processing method of FMCW radar is analyzed. Aiming at the problem that the distance and velocity unit gap is too large, method that applies QFM to radar signal processing is proposed. We introduce the QFM and derive the error formula by using QFM to estimate frequency value. The simulation and real data processing show that the derived error formula is right and the method can weaken the step effect of distance and velocity. More importantly, the method can be applied to real-time processing because it only adds a small amount of computations.

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