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24 GHz FMCW Radar Systems for Blind Spot Detection System

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Abstract : This paper is devoted to analysis of frequency modulated continuous wave (FMCW) radar system for safety driving application, namely, blind spot detection (BSD) system. We introduce FMCW radar with 24 GHz operating frequency as the best solution for BSD system. This paper has two main goals. The first goal is to define why the 24 GHz FMCW radar system is the most suitable for the BSD. The second goal is to draw up the FMCW radar system signal detection and processing algorithm design steps for BSD system.

Key words : Blind spot detection(BSD), Frequency modulated continuous wave(FMCW) radar, Range-velocity processing, Signal detection and processing algorithm design steps.

1. INTRODUCTION

The Safety Driving System (SDS) is the output of the integration between information and communications technologies with the transport infrastructure and vehicles to manage the traffic, improve the safety, reduce the transportation times, and, also, the fuel consumption. Various technologies are applied by different safety driving systems, for example, radar sensors system, laser sensors (LIDAR), ultrasonic sensors, vision cameras, etc.

The blind spot is the viewing angle area on the rear left and right sides of a vehicle that is not covered by the internal and external regular mirrors (see Fig. 1).[1]

The biggest blind spot is located over a driver right shoulder between the edge, where the peripheral vision ends, and the area up to the back of the car that is not seen in the side mirror. The left side blind spot is smaller and should be checked, too.

The blind spot detection (BSD) system requires a small detection area with a maximum range of 5m (up to 15m) at the location of the car blind spot.[2] The lane change assistant system can be considered as the logical extension of the BSD system.

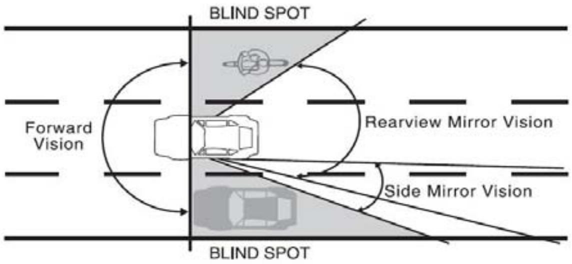

Fig. 1 Blind Spot definition.

The main purpose of this paper is to achieve two main goals. The first goal is to define why the 24 GHz frequency modulation continuous wave (FMCW) radar system is the most suitable system for the BSD system. The second goal is to draw up the FMCW radar system signal detection and processing algorithm design steps for BSD system.

This paper is organized as follows: In section 2 the recommended 24 GHz FMCW radar sensor system is described. Section 3 presents the signal processing algorithm for BSD system. Section 4 introduces the FMCW signal detection and processing algorithm design steps. In section 5 we present some conclusions.

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2. 24 GHz FMCW RADAR SENSOR SYSTEM

2.1 Why we use FMCW radar sensor system for BSD

FMCW radar is usually used for all radar sensor system applications in different range classification (long, middle, short) because it can be easily implemented and the requirements for antenna power are lower in comparison with other radar sensor systems when the high accuracy of measurement is required.

The main advantages of the FMCW radar sensor system implementation are: 100% duty cycle, simple bandwidth implementation requirements , hardware complexity is low. A comparison between FMCW and pulse radar sensor systems is very useful to understand the advantages of FMCW radar sensor system. In the present time, the most of radar companies produce FMCW or pulse radar sensor system.

The pulse Doppler radar sensor system is more suitable for long-range detection, while FMCW radar sensor system is more appropriate for short/middle-range detection. In the case of BSD, we need a short range detection system, for example, from 0.5 meter to 15 meter. Because of this, the FMCW radar sensor system is more suitable for BSD system.

The advantages of FMCW radar system over pulse radar system, can be summarized as follows:

- Less complex in spite of full duplex;
- Better performance for short and middle range detection;
- Better resolution for range and lower cost;
- Low false alarm rates;
- Small beam-width

2.2 Why we use 24 GHz as FMCW radar operation frequency

BSD system is a short range radar (SRR) system with a maximum range of 15m (up to 20m).

The 24 GHz SRR technology allows us to achieve low-cost design, and keeps the radar sensor network size small enough to fit even in a small available space while providing useful range resolution and object separation values.

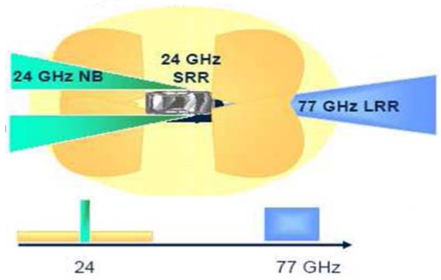

Fig. 2 Present safety system concept

According to the atmospheric conditions, the attenuation factor is a function of frequency and is presented in the Fig. 3 for air at 20°C and 7.5 g/m^2 moisture content. As we can see from Fig. 3 attenuation performance is dependent on pressure, temperature, and relative humidity.

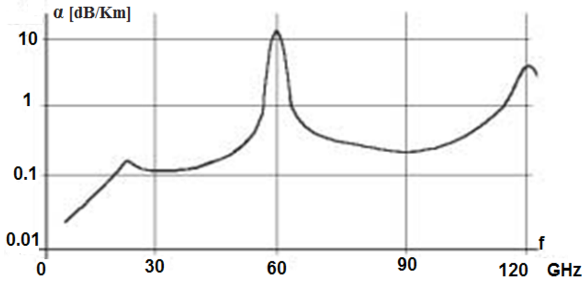

Fig. 3 The relation between the attenuation factor and the frequency

From Fig. 3 we can see that the attenuation factor α is smaller under comparison with attenuation ones for other values of radar operation frequency.

The choice of the 24 GHz as operating frequency allows us to obtain less attenuation in comparison with other operating frequencies, for example, 45GHz, 76GHz, 77GHz, 95GHz, and 120GHz.

The 24 GHz is considered as the best compromise for functionality, size, performance, cost, hardware complexity, and integration in vehicle. SRR signal carrier frequency is allocated within the limits of the interval 24.050 GHz to 24.250 GHz. Under selection of 24 GHz, manufacturers have to take the following factors into consideration: the propagation loss at 24 GHz, the directed and narrow beam width (for elevation) as well as the very low power of the modulation sidebands. SRR sensors do not require long range capability. [4)]

3. SIGNAL PROCESSING ALGORITHM

Using the linear modulated chirp signals, for example, the saw-tooth wave, triangular wave, and trapezoidal wave, it is possible to define and estimate the relative velocity and distance between the subject vehicle (SV) and the target vehicle (TV). The basic structure of the FMCW radar sensor waves is presented in Fig. 4.[5)]

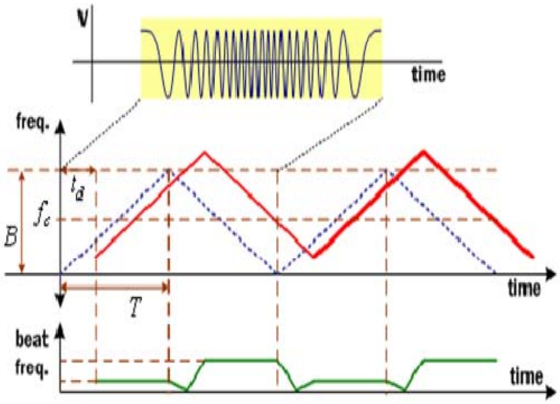

Fig. 4 Triangular wave of FMCW radar.

The frequency difference between the transmitted and target return signals is the beat frequency. In the case of stationary TV, the beat frequency has the constant value.

3.1 FMCW radar sensor system waveforms

In this section, the waveforms of the transmitted and target return signals are discussed. In general, when we need to define the TV relative velocity with respect to SV it is useful to employ a triangular waveform. This special waveform shape is used to eliminate the ambiguity of TV range and velocity.

The up-sweep part of transmitted signal is defined in the following form:

$$T_{up}(t) = \cos\left[2\pi\left(f + \frac{1}{2}\frac{B}{T_c}t\right)t\right], \qquad (1)$$

where f is the FMCW radar sensor system operation frequency; B is the sweep bandwidth; and T_c is the sweep time. The ratio between the sweep bandwidth and sweep time is called the frequency modulation slope and denoted by μ:

$$\mu = \frac{B}{T_c}. \qquad (2)$$

Under this presentation of the up-sweep transmitted signal we consider the transmitted signal has the unit amplitude and zero initial phase.

The basic idea is to generate a linear frequency ramp with bandwidth B (for a single ramp) and duration T_c. In this case, the frequency can be defined as:

$$f(t) = f + \frac{B}{T_c}t. \qquad (3)$$

Under the optimal transmission conditions that the transmitted signal is free from interference and noise, the TV return signal is affected by delay and Doppler shift. Thus, the target return signal can be presented as follows:

$$R_{up}(t) = \cos\left[2\pi\left(f + \frac{1}{2}\frac{B}{T_c}\left(t - \tau - \frac{2V}{c}t\right)\right)\left(t - \tau - \frac{2V}{c}t\right)\right] \qquad (4)$$

where τ is the delay (round trip time to the TV) given by

$$\tau = \frac{2R}{c}, \qquad (5)$$

where R is the TV range; V is the relative velocity; and c is the velocity of electromagnetic wave propagation.

Figure 5 shows the transmitted and target return signal waveforms of the FMCW radar sensor system.[6)]

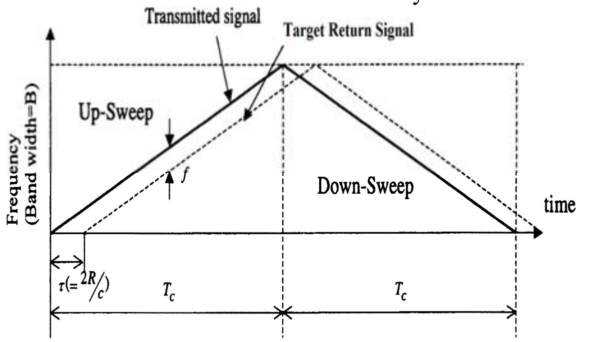

Fig. 5 FMCW radar sensor transmitted and target return signal waveforms.

In the FMCW radar receiver, the target return signal is down-converted by mixing it with the transmitted signal, i.e. multiplying in the time domain and after that the obtained sum frequency signal, approximately with twice carrier frequency, is eliminated by low pass filter (LPF). Thus, the final signal is obtained and can be determined in the following form:

$$B_{up}(t) \cong \cos\left(2\pi\left(-\frac{2B}{cT_c}R - \frac{2V}{\lambda}\right)t\right), \qquad (6)$$

where $\lambda = \frac{c}{f}$ is the wavelength of the transmitted signal.

The Q-channel beat signal is obtained by mixing the target return signal $R_{up}(t)$ with the following sinusoid signal:

$$S(t) = \sin\left[2\pi\left(f + \frac{1}{2}\frac{B}{T_c}t\right)t\right]. \qquad (7)$$

The complex beat signal of the up-sweep transmitted signal is obtained after combining the I-channel and Q-channel beat signals, and this signal can be presented in the following form:

$$B_{up}(t) \cong \exp\left(2\pi j\left(-\frac{2B}{cT_c}R - \frac{2V}{\lambda}\right)t\right). \qquad (8)$$

By following the same steps, the complex beat signal of the down-sweep transmitted signal can be obtained. This signal can be written in the following form:

$$B_{down}(t) \cong \exp\left(2\pi j\left(\frac{2B}{cT_c}R - \frac{2V}{\lambda}\right)t\right) \qquad (9)$$

3.2 The target return signal parameters and range and velocity definition.

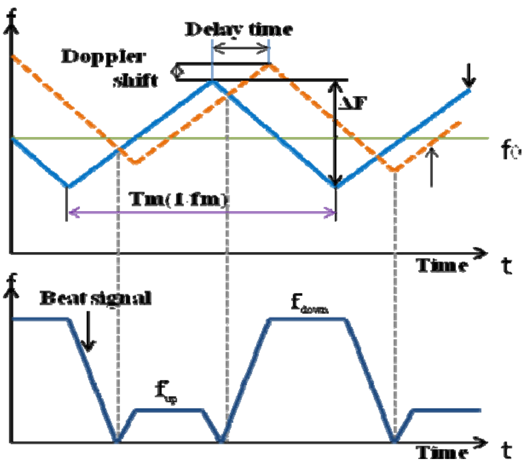

Fig. 6 Beat signal of the FMCW radar sensor system.

The main required parameters for BSD applications, namely, TV range and velocity, can be obtained from the beat signal frequency. The beat signal frequency is composed of the TV range and the velocity. In the FMCW radar sensor receiver, the frequency analysis is applied to sample of the beat signals $B_{up}(t)$ and $B_{down}(t)$ in order to define the peak frequencies. Figure 6 presents the beat signals of the transmitted and target return signals for FMCW radar sensor system.

The peak frequency or beat frequency of the up-sweep part of the transmitted and target return signals can be determined in the following form:

$$f_{up} = \left(-\frac{2B}{cT_c}R - \frac{2V}{\lambda}\right). \qquad (10)$$

By the same way we can define the peak frequency of the down-sweep part of the transmitted and target return signals as follows:

$$f_{down} = \left(\frac{2B}{cT_c}R - \frac{2V}{\lambda}\right). \qquad (11)$$

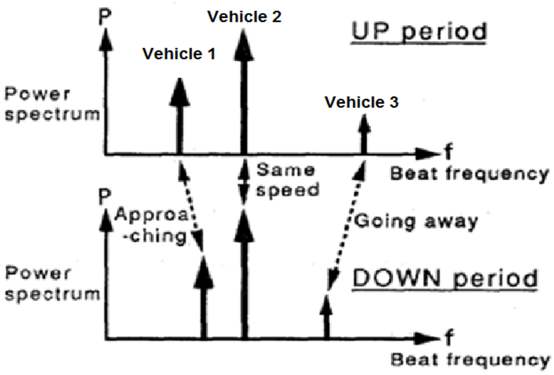

Fig. 7 Beat signal spectrum.

Thus, the required target parameters can be defined based on the up and down peak frequencies (the beat frequencies). The beat signal spectrum analysis (see Figure 7) in the up-sweep and down-sweep gives us a mechanism how to decide whether TV is approaching SV, going away or having the same speed.

The TV range using the beat frequencies can be determined in the following form:

$$R = -\frac{cT_c}{4B}\left(f_{up} - f_{down}\right). \qquad (12)$$

The velocity can also be defined using the beat frequencies in the up and down sweeps in the following form:

$$V = -\frac{\lambda}{4}\left(f_{up} + f_{down}\right). \quad (13)$$

The azimuth angle definition and measurement performance are independent of the FMCW radar sensor waveform. The antenna design can be an important factor affecting the azimuth angle detection. Radar sensors network is also possible solution to define the position and the azimuth angle of the TV.

4. The LFMCW SIGNAL PROCESSING ALGORITHM DESIGN STEPS

The process of signal detection algorithm design is an essential element to develop the digital signal processing (DSP) for car applications. To a large degree, the signal detection algorithm design has a significant impact on the performance and functionality of the radar sensor system. Radar engineers must define the mathematical function that is able to meet the application or the product requirements to ensure the signal detection algorithm compatibility. In the previous discussion, we should divide the signal detection process into three levels:

- The first level: the basic level –the main principles similar for all radar sensor systems;
- The second level: the waveform and the predefined parameter formulas;
- The third level: the operational processing algorithm and any sub-algorithms, namely, error correction, noise cancellation, radio frequency interference and so on.

The main signal detection and processing algorithm design stages are:

- The initial selection of the prototypical algorithm;
- The manipulation and analysis of the selected algorithm;
- The exploration of input/output parameters;
- Sub-algorithms assignment for sub-problems or requirements for complete solution;
- The performance improvement description as the final result.

For BSD applications, the design steps can be presented in more detail based on the baseline detector definition as follows:

Baseline detector: the first step is about to define the initial conditions, to choose the basic radar sensor detecting technology (baseline detector), and, also, the initial selection of the signal processing algorithm framework, and the symbolic and numerical description of the selected signal detection algorithm.

Theoretical investigation; theoretical investigation is the main body of the design, and includes the theoretical analysis of the detection performance and improvement of signal processing algorithm for the radar sensor systems. The signal detection algorithm design includes:

- The waveform design;
- The modification of the signal processing algorithm;
- False alarm management (adjust the threshold of the radar return signal power);
- Target detection: the probability of detection P_D and the fixed probability of false alarm P_F;
- The sub-algorithms and any practical operations would be needed to solve some problems, eliminate the errors, and cancel the interference and noise; for this purpose, there is a need to have a complete radar sensor system;
- The problem to find an alternative of signal detection algorithm description that means to find all the identity transformations applicable to the signal detection and processing;
- Computer costs under the use of signal processing and detection algorithms in radar sensor systems.

Performance Comparison: The final step in the process to design signal detection algorithm is to confirm the performance improvement of the radar sensor system in comparison with modern radar sensor systems for BSD applications.

Empirical Performance: The emphasis on signal detection and processing perspectives enables us to understand better the advantages and disadvantages of each signal detection and processing algorithm, avoid unrealistic performance expectations, and apply an algorithm properly and sensibly.

5. CONCLUSION

The 24 GHz FMCW radar sensor system for the BSD safety driving application is come after a review analysis of the radar sensor systems that has been done to compare and analyze the radar sensor systems in order to define the most appropriate one for BSD system.

According to the previous discussion devoted to 24 GHz FMCW radar for BSD system, the next step is to carry out a complete and deep analysis for the chosen radar sensor system and investigate the best ways to design and map all the possible methods to improve the detection performance. Following the presented signal detection and processing algorithm design steps it is possible to reach the best performance.

An important part of this research is to know the current limitations in performance of the recommended FMCW radar sensor system to satisfy the required specifications to BSD system.

Acknowledgement

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