FMCW Multipulse Radar System For Improved Vehicle Speed Detection Capabilities

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***Abstract*—Accidents on toll roads are often caused by vehicles exceeding the legal speed limit. To mitigate this, a reliable speed detection system is required—one that offers a wide detection range, high accuracy, and the flexibility to be integrated into a vehicle's body. One promising solution is the use of Doppler radar based on the Frequency-Modulated Continuous-Wave (FMCW) principle. However, traditional FMCW radars face significant challenges in detecting low-speed motion due to the extremely small Doppler frequency shifts involved. This paper proposes an enhanced vehicle speed detection method using a multipulse FMCW radar system. The multipulse technique divides a single signal period into multiple short pulses, increasing spectral sampling density and improving Doppler resolution. MATLAB based simulation results demonstrate that the system can accurately detect speeds as low as 4 km/h by producing sharper and more distinguishable Doppler spectral peaks. The proposed approach shows strong potential for real-time traffic monitoring and intelligent transportation systems.**

Keywords—FMCW radar, doppler effect, multipulse, vehicle.

I. INTRODUCTION

Vehicles exceeding the maximum permitted speed are a leading cause of traffic accidents, particularly on toll roads. Although authorities continue to enforce speed limits, many existing speed detection technologies remain limited especially in short-range applications and low-speed scenarios. A reliable and precise system is needed to monitor vehicle velocity across a wide range, ideally one that can be integrated into the vehicle for real-time response and safety intervention. Obtaining accurate speed data is essential to anticipate safety risks, particularly during braking and close-range maneuvering.

Doppler radar offers a promising solution by leveraging frequency shifts in reflected signals to measure target velocity [1]. When installed at the front or rear of a vehicle, it enables continuous monitoring and can trigger safety actions, such as warnings or automatic braking. However, detecting low-speed motion remains challenging, as the resulting Doppler frequency shifts are extremely small and prone to noise [2]. The Doppler effect highly depends on the frequency and the target's speed. The resulting frequency shift is minimal and difficult to detect at low speeds. Nevertheless, accurately measuring speed at low velocities is crucial, especially during braking, to ensure safety.

In previous studies, low-cost continuous-wave (CW) Doppler radar systems have been implemented using microcontrollers such as Arduino and radar modules like the HB100 to detect vehicle speed based on the Doppler Effect [3]. While these systems are simple and cost-effective, they present several limitations. Notably, CW radar cannot measure the distance to the target; it only detects the relative speed along the radar's line of sight. Furthermore, its accuracy drops significantly when the target is not moving directly toward the radar beam, due to the cosine angle error [4]. CW systems also struggle to detect low-speed motion because the Doppler frequency shifts are very small and often buried in noise. In addition, they are highly susceptible to interference from surrounding moving objects [5].

This research proposes using a Frequency Modulated Continuous Wave (FMCW) multipulse radar, which detects speed and accurately measures the distance to the target. This technology enables simultaneous range and velocity measurement with higher accuracy, especially at low speeds, and significantly reduces cosine-related errors. In addition, FMCW radars support range-Doppler mapping and multi-target tracking, offering a more robust and adaptive solution for modern traffic safety applications.

II. FMCW MULTIPULSE

A. Radio Detection and Ranging

Radio Detection and Ranging, or abbreviated as RADAR, is a system or device that uses electromagnetic waves in radio frequencies that function to detect distance, direction, speed, and characteristics of a subject, whether the subject is moving or stationary [6]. The main advantage of radar is that microwaves can penetrate several objects and detect objects that cannot be seen. Radar can function at close or long distances and in conditions resistant to optical and infrared sensors. In dark, rainy, foggy, or snowy conditions, the radar can continue to operate to measure distance with high accuracy [7] .

B. Frequency Modulated Continuous Wave (FMCW)

Frequency Modulated Continuous Wave (FMCW) radar is a radar system that transmits electromagnetic signals continuously [8]. The frequency of this signal will continue to change over time within the set bandwidth sweep. In addition, FMCW radar can utilize frequency modulation to detect an object. When utilizing frequency modulation, the signal received by the radar has a different frequency than that transmitted due to the delay [9].

C. Doppler Effect

The Doppler Shift effect is the shift in frequency between the receiver signal and the transmitter signal [10]. The Doppler effect on radar systems is used to measure speed. The basic principle of Doppler radar is where the radar emits a transmit signal to hit the target, then the waves will be reflected back to the radar (echo signal) to measure the magnitude of the frequency shift that occurs. The magnitude of the frequency shift is the Doppler frequency used to determine the target speed of the moving target [11]. The Doppler frequency will have a positive value if the target is close and will have a negative value on the other hand.

When a vehicle moves toward or away from the radar, the frequency of the reflected signal will shift due to the Doppler effect [12]. This frequency shift can be calculated using the Doppler equation:

$$f_d = \frac{2v\, f_0 \cos\theta}{c} \quad (2.1)$$

Where f_d denotes the Doppler frequency in hertz (Hz), v represents the speed of the vehicle in meters per second (m/s), f_0 is the frequency of the transmitted radar signal in hertz (Hz), θ is the angle between the radar's line of sight and the direction of the vehicle's motion, and c is the speed of light in a vacuum, approximately equal to 3×10^8 meters per second [13].

If the vehicle moves directly toward or away from the radar θ = 0, then cosθ=1, and the equation simplifies to:

$$f_d = \frac{2v\, f_0}{c} \quad (2.2)$$

Thus, the vehicle speed can be derived from the measured Doppler frequency:

$$v = \frac{f_d \cdot c}{f_0} \quad (2.3)$$

D. Multipulse

Multipulse, or multi-chirp, in FMCW radar refers to transmitting multiple consecutive chirps within a single data acquisition cycle. Each chirp generates range data through frequency domain analysis (FFT), and the sequence of chirps is then analyzed across time to extract the target's velocity information via Doppler analysis. This technique enables the construction of a two-dimensional map (range-Doppler map) that simultaneously represents the position and velocity of objects. Such mapping is essential for systems that must detect multiple targets simultaneously (multi-target detection), such as in automotive radar and traffic surveillance systems.

In a multipulse radar system, a series of pulses is transmitted at specific time intervals (Pulse Repetition Interval, PRI) [14]. Each reflected pulse will exhibit a phase shift that depends on the motion of the target. The phase difference between pulses (Δϕ) can be used to calculate the target's speed using the following relation:

$$\Delta\phi = \frac{4\pi v T\, f_0}{c} \quad (2.4)$$

Where Δϕ represents the phase shift between consecutive radar pulses, and T denotes the time interval between those pulses, measured in seconds.

This can be rearranged to calculate vehicle speed from phase difference:

$$v = \frac{\Delta\phi \cdot c}{4\pi T f_0} \quad (2.5)$$

This method enables speed measurement without requiring continuous waveform tracking, relying instead on the phase shift between discrete pulses.

The multiposition technique in Doppler radar is an approach in which the Doppler radar is used from several different positions or angles to measure the relative speed and direction of movement of the target [15]. By using multiple positions or angles of observation, this technique makes it possible to produce more accurate data on the relative motion of the target compared to the use of a single Doppler radar. The improved signal processing from the pulse-Doppler allows small, high-speed objects to be detected at close range with large, slow-moving reflectors.

E. Vehicle Speed

The minimum and maximum speed limits on different types of roads and for different types of vehicles may vary, depending on the traffic regulations in force in each country. In Indonesia, the highest speed limit permitted is 130 km/h, while the lowest speed limit is set at 20 km/h.

III. EXPERIMENTAL METHOD AND MODEL DESIGN

A. Proposed Method Design

This research was carried out by designing a multipulse detection method using a 24 GHz FMCW radar to obtain the speed and distance of the vehicle with a system consisting of the FMCW radar itself and the processing of the data received by the radar.

In relation to vehicles, when we want to detect from time to time, including in vehicles, what is used is a moving radar because the radar is placed on a moving object, namely the vehicle body, shot at a static object, namely the vehicle's road trajectory, then it will produce a Doppler effect, how much Doppler frequency can be detected later and will gain speed.

B. Simulation Model

Simulation is carried out using computer simulation with the aim of proving the truth of scientific concepts obtained from the research conducted. Furthermore, the success of the simulation process can be the basis that the concepts obtained can be implemented. The requirements and parameters used in the simulation are listed in the following table.

TABLE 1
Simulation Parameters

Description	Value
Frequency	24 GHz
Bandwidth	100 MHz
Minimum Speed	20 km/h
Maxsimum Speed	130 km/h

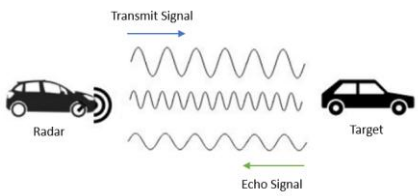

FIGURE 1
Data collection scenario 1

FIGURE 2
Data collection scenario 2

Figure 3.2 illustrates the mechanism of an automotive radar detecting an object in front, specifically another vehicle. The radar transmits a signal forward and receives the reflected (echo) signal from the target vehicle to estimate its relative distance and speed. Meanwhile, Figure 3.3 shows a condition where the radar is directed toward the road surface with no moving object present. The reflection from the static road serves as a background reference to distinguish between echoes from moving targets and those from the static environment.

C. *MATLAB Simulation Model*

Figure 3.4 illustrates the flowchart of the MATLAB simulation process for the multipulse FMCW radar system.

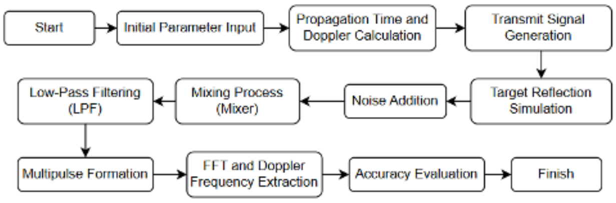

FIGURE 3
MATLAB Simulation Flowchart for the FMCW Multipulse Radar System

The simulation stage can be seen in Figure 3.4. The radar simulation begins with the input of key parameters such as operating frequency, signal bandwidth, target speed and distance, angle of arrival, number of pulses (N), and the signal-to-noise ratio (SNR). Based on these parameters, the system calculates signal propagation time and Doppler frequency shift. The radar then generates a chirp signal as the transmitted waveform (output: SCtx), which is reflected by the target to produce a received signal (output: SCrx). Noise is added to simulate environmental conditions (output: SCrxT).

The noisy reflected signal is then mixed with the reference signal to produce a beat signal (output: Smix), which is passed through a low-pass filter to extract the baseband signal (output: SLpf). This signal is further structured into a multipulse format (output: SCrxm) and processed using the Fast Fourier Transform (FFT) to extract the Doppler spectrum and estimate the target's speed (output: Sofft). System accuracy is evaluated by comparing the estimated results with theoretical values, and all simulation outputs are presented in both numerical and graphical formats for further analysis.

In a multipulse FMCW radar system, velocity resolution (Δv) is a crucial parameter that indicates the system's ability to distinguish between two targets moving at slightly different speeds. A smaller Δv value means the radar has a higher sensitivity to small velocity changes, which is particularly important for detecting slow-moving objects.

The value of Δv is derived from the Doppler frequency resolution (Δf) obtained from the FFT output and converted to velocity using the following formula:

$$\Delta_v = \frac{c.\Delta_f}{2f_0} \quad (3.1)$$

where:

c = speed of light (≈ 3 × 10^8 m/s),

Δf = Doppler frequency resolution (Hz),

f0 = radar operating frequency (24 GHz).

Simulation results show that increasing the number of pulses (N) improves velocity resolution. As N increases, the spacing between Doppler spectral peaks (Δf) decreases, resulting in a smaller Δv. This indicates that the system becomes more sensitive to small velocity variations.

IV. RESULTS AND ANALYSIS

A. *Simulation Results*

The simulation is carried out with a matlab simulation by referring to the actual conditions of the vehicle. The parameters used have been presented in table 3.1. In this simulation, a minimum bandwidth 100 MHz with an operating frequency of 24 GHz is used. Using equation 2.1, the simulation process will be limited to a minimum vehicle speed of 20 km/h and a maximum speed of 130 km/h.

In a multipulse FMCW radar system, the performance of speed detection is influenced by three main parameters: the number of pulses (N), the signal-to-noise ratio (SNR), and the incident angle (θ).

1. Number of Pulses (N):

A higher N improves Doppler resolution and speed estimation accuracy. This study uses N = 8 as it offers an optimal balance between spectral sharpness and computational efficiency.

2. Signal-to-Noise Ratio (SNR):

A high SNR provides clearer Doppler spectra and more reliable speed estimates. Therefore, an SNR of 40 dB is used to reduce noise interference and enhance peak clarity.

3. Incident Angle (θ):

The incident angle affects the detected velocity component. At 60°, only about 50% of the actual speed is measured, but this angle was chosen to reflect realistic roadside radar placement.

At a minimum speed of 20 km/h, the following results were obtained:

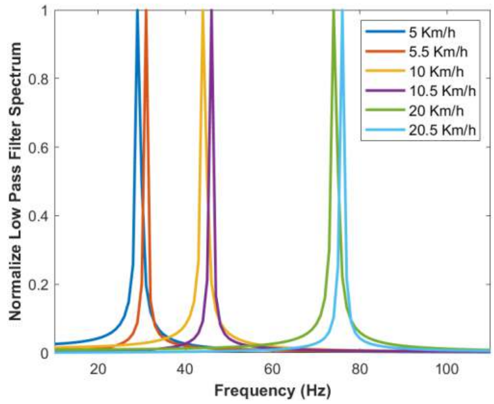

FIGURE 4
Detectio results of the dopller shift for two different target speed using single pulse technique

Figure 4.1 shows the result of doppler shift for detection of low-speed movement, using single pulse technique. The frequency spectrum for small different speed is overlapping and causes difficulty in detecting the peak spectrum frequency difference. The multipulse technique than proposed to overcome the limitation of singlepulse technique in detecting the doppler frequency, especially in low-speed movement monitoring that usually need in breaking processes.

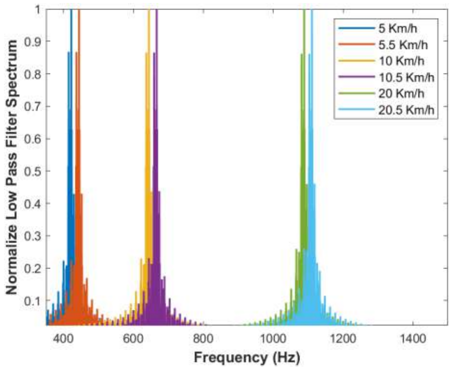

FIGURE 5
Detectio results of the dopller shift for two different target speed using multipulse technique.

Figure 4.2 shows the simulation results after implementing the multipulse technique in detecting the doppler in low-speed movement condition. The used of multipulse radar signal causes sampling in the spectrum of low pass filter output and it exhibit in increasing the resolution in detecting the peak spectrum difference for two different low-speed movement. This technique can resolve the problem on spectrum overlapping that appears in Figure 4.1.

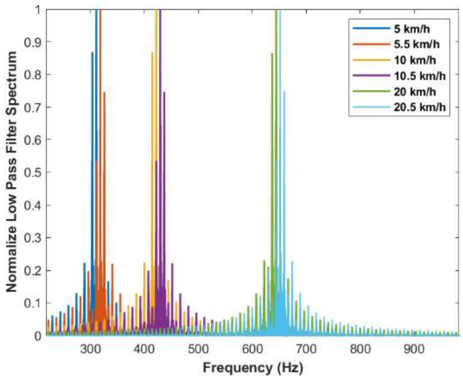

FIGURE 6
Detection results of the Doppler shift for two different target speeds using the multipulse technique at an incident angle of 60 degrees.

In Figure 4.3, an incident angle of 60 degrees is applied. The observed Doppler shift is lower than in the ideal case because it depends on the cosine of the incident angle (cos θ). As the angle increases, the detected velocity component decreases, which in turn reduces the accuracy of the velocity estimation. A larger incident angle results in a smaller Doppler frequency, causing the estimated speed to be lower than the actual target velocity.

At a maksimum speed of 130 km/h, the following results were obtained:

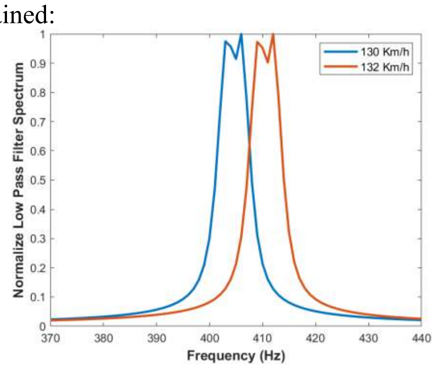

FIGURE 7
Detectio results of the dopller shift for two different target speed using single pulse technique.

Figure 4.3 shows the graph of the results of the target speed simulation that will be detected at the high vehicle speed condition, which is 130 km/h. The overlap frequency spectrum of low pass filter output for small different speed is also occurred and it make difficulty in detecting the peak spectrum difference.

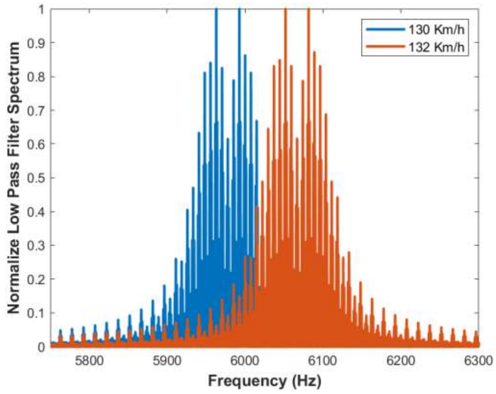

FIGURE 8
Detectio results of the dopller shift for two different target speed using multipulse technique

Figure 4.4 shows the simulation results after implementing the multipulse technique in detecting the doppler in low-speed movement condition. The used of multipulse radar signal causes sampling in the spectrum of low pass filter output and it exhibit in increasing the resolution in detecting the peak spectrum difference for two different low-speed movement. This technique can resolve the problem on spectrum overlapping that appears in Figure 4.3.

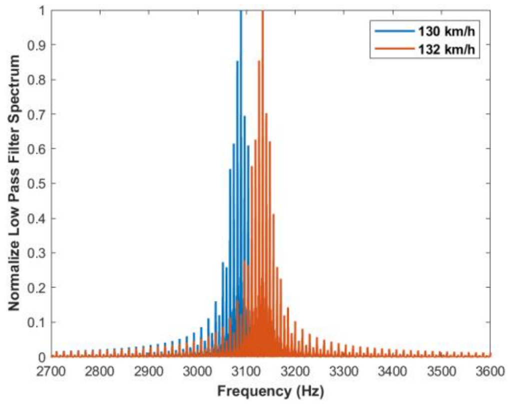

FIGURE 9
Detection results of the Doppler shift for two different target speeds using the multipulse technique at an incident angle of 60 degrees.

In Figure 4.6, an incident angle of 60 degrees is applied. The observed Doppler shift is lower than in the ideal case because it depends on the cosine of the incident angle (cos θ). As the angle increases, the detected velocity component decreases, which in turn reduces the accuracy of the velocity estimation. A larger incident angle results in a smaller Doppler frequency, causing the estimated speed to be lower than the actual target velocity.

V. CONCLUSIONS

A. Conclusions

This study demonstrates that the FMCW radar system with a multipulse technique significantly improves vehicle speed detection accuracy, especially at low speeds. Dividing one period into multiple pulses enhances spectral resolution, allowing more accurate detection of Doppler frequency shifts caused by target motion. A higher number of pulses produces sharper spectral peaks, resulting in more precise speed estimation. Simulation results show that using 8 pulses (N = 8) offers the best balance between spectral clarity and computational efficiency. The system can detect speeds ranging from 4 to 200 km/h, with an SNR of 40 dB and an incident angle of 60°, providing reliable speed detection and high Doppler resolution.

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