A Novel Calibration Method for Dual-channel Doppler Radar Sensor of High-speed Train

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Abstract. Based on the working principle of dual-channel Doppler radar sensor mounted at high-speed train, the shortcomings of the traditional calibration method for dual-channel Doppler radar sensor are analysed and a novel calibration method based on the dual Doppler shifts simulation method is proposed in this paper. A simulator is specifically designed and realized to verify the proposed novel calibration method. The simulated speed range of the simulator is up to (5–500) km/h and the MPE is ±0.05 km/h, which can fully satisfy the calibration requirements of dual-channel Doppler radar sensor. The calibration results of a selected sample validate the effectiveness and feasibility of the novel calibration method.

1. Introduction
Speed surveillance is a key factor to ensure the safety, high speed and high efficiency of the moving high-speed train. In order to meet the requirement of being safer and faster for high-speed rail, two dual-channel Doppler radar sensors are also mounted at high-speed train besides of conventional axle-mounted wheel speed sensors and pick-up speed sensors to measure the instantaneous speed of high-speed train because of their advanced performances, safety and reliability. To ensure the speed measurement result accurate and reliable, every dual-channel Doppler radar sensor must be calibrated before being mounted at high-speed train. However, traditional calibration method presently used can’t fully meet the calibration requirements of dual-channel Doppler radar sensor [1]. A novel calibration method for dual-channel Doppler radar sensor is proposed based on the dual Doppler shifts simulation method in this paper. This paper is organized as follows. Section 2 introduces the working principle of dual-channel Doppler radar sensor. Section 3 introduces the traditional calibration method and describes the proposed novel calibration method for dual-channel Doppler radar sensor. Section 4 provides the calibration results of a selected sample to validate the novel calibration method. Section 5 concludes the paper.

2. Working principle of Dual-channel Doppler Radar Sensor
Dual-channel Doppler radar sensor (DDRS) measures the instantaneous speed of high-speed train based on the Doppler effect principle [2]. As shown in Figure 1(a), DDRS mounted at high-speed train moves along the railway at a speed value $v$, and its dual-antenna beams respectively point to the rail surface at fixed angles $\phi_1$ and $\phi_2$, which are called nominal beam pointing angles and respectively defined as the included angle between the direction of movement speed and the two nominal directions of dual-antenna beams. DDRS emits two individual single-frequency continuous-wave

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(SFCW) microwave signals with nominal emitted frequencies $f_1$ and $f_2$ to the railway at the same time, and receives two individual echo signals reflected from the rail surface. The frequency difference between the emitted signal and the received one is called the Doppler shift, where two Doppler shifts $f_{d1}$ and $f_{d2}$ of DDRS can be respectively expressed as [2]

$$\begin{cases}
    f_{d1} = \frac{2}{C} \cdot f_1 \cdot v \cdot \cos \theta_1, \\
    f_{d2} = \frac{2}{C} \cdot f_2 \cdot v \cdot \cos \theta_2,
\end{cases} \quad (1)$$

where $C$ is the speed of electromagnetic wave propagating in air, and $\theta_1$ and $\theta_2$ are called the actual beam pointing angles and respectively defined as the included angle between the direction of movement speed and the actual directions of antenna beams as shown in Figure 1.

![Figure 1](image)

**Figure 1.** The simplified schematic diagram of working principle of DDRS: (a) In the ideal situation without installation deviation; (b) In the actual situation with installation deviation.

In the ideal situation without installation deviation as shown in Figure 1(a), $\theta_1 = \varphi_1$ and $\theta_2 = \varphi_2$, both of which are known values. However, installation deviation is obviously inevitable in the actual situation. Supposing there is an installation deviation angle $\Delta \varphi$ when the DDRS is mounted at high-speed train as shown in Figure 1(b), then $\theta_1 = \varphi_1 - \Delta \varphi$ and $\theta_2 = \varphi_2 - \Delta \varphi$, both of which are variable values because of the unknown $\Delta \varphi$. According to equations set (1), the true value of movement speed $v$ can be written as

$$\begin{cases}
    v = \frac{C}{2} \cdot f_{d1} / f_1 \cdot \cos(\varphi_1 - \Delta \varphi), \\
    v = \frac{C}{2} \cdot f_{d2} / f_2 \cdot \cos(\varphi_2 - \Delta \varphi).
\end{cases} \quad (2)$$

Therefore, the true value of movement speed $v$ and installation deviation angle $\Delta \varphi$ can be accurately calculated by solving the above equations set (2). So DDRS has the ability to compensate the effect of installation deviation on the speed-measuring accuracy and measure the true value of movement speed in the actual situation.

### 3. Calibration method

To ensure its speed measurement result accurate and reliable, DDRS must be calibrated before being mounted at high-speed train. Calibration is usually carried out by simulation methods in the laboratory. **3.1. Traditional method**

Traditional calibration method for DDRS is based on the principle of relative motion by using a moving pavement simulator as shown in Figure 2(a). The moving pavement simulator is composed of a motor, a driving wheel, a driven wheel, a mesh belt, a controller, an encoder, and so on [3]. DDRS under test is fixedly installed directly above the moving pavement simulator. The mesh belt of the simulator moves at the intended linear speed value $v$ converted from the rotational speed of the driving wheel and the driven one, drove by the motor and controlled by the controller. According to the relative motion principle, the above traditional calibration method is equivalent to the DDRS under test mounted at high-speed train moves along the railway at a speed value $v$. 


The traditional method simulates the work scene of DDRS by using the moving pavement simulator and calibrates the DDRS under test in a mechanical way. However, the maximum speed value of the simulator is just 50 km/h because of the restrictions of system performance and personal safety, and the maximum speed-measuring value of DDRS is usually up to 500 km/h. So the traditional method can’t meet the calibration requirements of DDRS in full range.

![Image](image.png)

**Figure 2.** Calibration methods for DDRS: (a) Traditional method; (b) Novel method.

### 3.2. Novel method

The block diagram of the novel calibration method is shown in Figure 2(b). The novel simulator is composed of two groups of dual horn antennas, two target simulators, computer, and so on. The principle of the novel calibration method is based on amplitude modulation (AM) of the emitted SFCW microwave signals from the dual-antenna of DDRS [2].

Firstly, enter the intended simulated speed value, motion direction and parameters of DDRS, and respectively calculate the two ideal Doppler shifts \( f_{d1} \) and \( f_{d2} \) according to equations set (1). And then two Doppler shift signals \( s_{d1}(t) = \cos(2\pi f_{d1}t) \) and \( s_{d2}(t) = \cos(2\pi f_{d2}t) \) are respectively generated by the two simulators.

Secondly, the SFCW microwave signals \( s_1(t) = \cos(2\pi f_1 t) \) and \( s_2(t) = \cos(2\pi f_2 t) \) emitted from the dual-antenna of DDRS are respectively received by the receiving antennas of two simulators and then are respectively amplitude modulated by multiplying \( s_{d1}(t) \) and \( s_{d2}(t) \). After filtering according the motion direction, two Doppler signals \( s_{d1}(t) \) and \( s_{d2}(t) \) are respectively generated by two simulators and can be expressed as

\[
\begin{align*}
  s_{d1}(t) &= \frac{1}{2} \cos[2\pi(f_1 + f_{d1})t] \\
  s_{d2}(t) &= \frac{1}{2} \cos[2\pi(f_2 + f_{d2})t]
\end{align*}
\]

or

\[
\begin{align*}
  s_{d1}(t) &= \frac{1}{2} \cos[2\pi(f_1 - f_{d1})t] \\
  s_{d2}(t) &= \frac{1}{2} \cos[2\pi(f_2 - f_{d2})t]
\end{align*}
\]

(3)

When the forward direction of motion is entered, the 1st equations set of (3) is chosen and the frequencies of two Doppler signals have been shifted to \( f_1 + f_{d1} \) and \( f_2 + f_{d2} \). When the backward direction of motion is entered, the 2nd equations set of (3) is chosen and the frequencies of two Doppler signals have been shifted to \( f_1 - f_{d1} \) and \( f_2 - f_{d2} \).

Finally, two Doppler signals are respectively remitted to the dual-antenna of DDRS by the emitting antennas of two simulators, and the intended simulated speed will be measured by DDRS. Record the measured value of simulated speed and calculate the simulated speed measurement error.

### 4. Calibration results

To verify the novel calibration method for DDRS, a dual Doppler shifts simulator is specifically designed and realized as shown in Figure 3(a). The novel simulator includes two target generators with the same parameters and computer, where the target generator integrates transceiver horn antennas and simulator as shown in Figure 2(b) together. The simulated speed range of target generator is up to (5–500) km/h and the maximum permissible error (MPE) of simulated speed is ±0.05 km/h, which can
satisfy the calibration requirements of DDRS with full range in the laboratory. The calibration process is shown in Figure 3(b). The type of the DDRS under test is DRS05/1a (S/N 15021305).

Figure 3. Calibration for DDRS under test: (a) Simulator; (b) Calibration process.

Table 1 shows the numerical calibration results for DRS05/1a at various intended speed points. Take the average of five independent measurement values as the measured value of simulated speed and calculate the simulated speed measurement error and relative error. It can be seen from Table 1 that all the relative errors are within the range of ±0.5% in full range of (10–500) km/h, validating the novel dual Doppler shifts simulation method as an effective calibration method for DDRS.

Table 1. Numerical calibration results.

| Speed (km/h) | Measurement Results (km/h) | Average (km/h) | Error (km/h) | Relative Error (%) |
|-------------|---------------------------|----------------|--------------|-------------------|
| 10.00       | 10.0                      | 10.0           | 0.0          | 0.0               |
| 60.00       | 60.1                      | 60.1           | 0.1          | 0.17              |
| 100.00      | 100.1                     | 100.1          | 0.1          | 0.10              |
| 200.00      | 200.2                     | 200.2          | 0.2          | 0.10              |
| 300.00      | 300.6                     | 300.6          | 0.6          | 0.20              |
| 400.00      | 400.8                     | 400.8          | 0.8          | 0.20              |
| 500.00      | 502.4                     | 502.4          | 2.4          | 0.48              |

5. Conclusion
This paper has introduced the working principle of DDRS mounted at high-speed train, analysed the shortcomings of the traditional calibration method for DDRS, and proposed a novel calibration method based on the dual Doppler shifts simulation method. A simulator is specifically designed and realized in this paper to verify the proposed novel calibration method for DDRS. The simulated speed range of the simulator is up to (5~500) km/h and the MPE is ±0.05 km/h, which can satisfy the calibration requirements of DDRS with full range in the laboratory. The calibration results of a DDRS sample validate that the novel dual Doppler shifts simulation method is an effective calibration method for DDRS in full range.

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