

VSWR BASED RAILWAY TRACK CRACK DETECTION AND PREVENTION SYSTEM USING HIGH FREQUENCY TRANSMISSION LINES

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Abstract: Railway safety critically depends on the structural integrity of tracks, where undetected cracks or fractures can result in derailments and severe casualties. This paper presents a Voltage Standing Wave Ratio (VSWR) based railway track crack detection and prevention system utilizing high-frequency transmission line principles. Railway tracks are modelled as transmission lines through which a controlled radio-frequency (RF) signal is injected. Structural discontinuities such as cracks, fractures, corrosion, or material degradation introduce impedance mismatches, leading to measurable changes in VSWR. The proposed system continuously monitors VSWR variations using an RF signal generator, directional coupler, VSWR sensing unit, and a microcontroller-based processing module. When abnormal VSWR values exceed predefined thresholds, the system generates real-time alerts and can initiate preventive actions by interfacing with railway signalling infrastructure. The system provides a continuous, non-invasive, and scalable solution for railway track health monitoring, reducing dependence on manual inspection and enhancing operational safety...

Keywords: Railway safety, crack detection, VSWR monitoring, transmission line faults, infrastructure health monitoring...

1. Introduction

Railway transportation is one of the most widely used and cost-effective modes of transport. However, the safety of railway operations is heavily influenced by the condition of the railway tracks. Track cracks caused by metal fatigue, corrosion, thermal stress, or excessive load are among the leading causes of derailments. Early detection of such defects is essential to prevent accidents and reduce maintenance costs. Conventional inspection techniques, including manual patrols, ultrasonic testing, and scheduled maintenance, provide only periodic assessment and often fail to detect faults at an early stage. These limitations motivate the need for a **continuous, automated, and real-time monitoring system**. In this paper, a VSWR-based fault detection approach is proposed, where the railway track itself is treated as a high-frequency transmission line. Impedance discontinuities caused by defects lead to reflections in the



RF signal, which are quantified using VSWR measurements. This approach enables non-invasive, continuous monitoring without disrupting railway operations.

2. Related Work

Several techniques have been reported for railway track defect detection, including ultrasonic inspection, eddy current testing, vibration analysis, and image-based methods. Ultrasonic testing is effective for internal crack detection but requires specialized equipment and periodic manual intervention. Vision-based methods depend on lighting conditions and require extensive image processing. Transmission line-based fault detection techniques have been widely used in power systems and communication cables. VSWR measurement is a well-established method for identifying impedance mismatches in RF systems. However, its application to railway track monitoring remains limited. This work extends transmission line fault detection concepts to railway infrastructure, providing a novel and practical solution for continuous monitoring.

3. System Architecture

The proposed VSWR-based railway track monitoring system consists of the following main components:

RF signal generator

Coupling interface

Railway track mode led as a transmission line

Directional coupler

VSWR measurement unit

Microcontroller-based processing unit

Alert and communication module

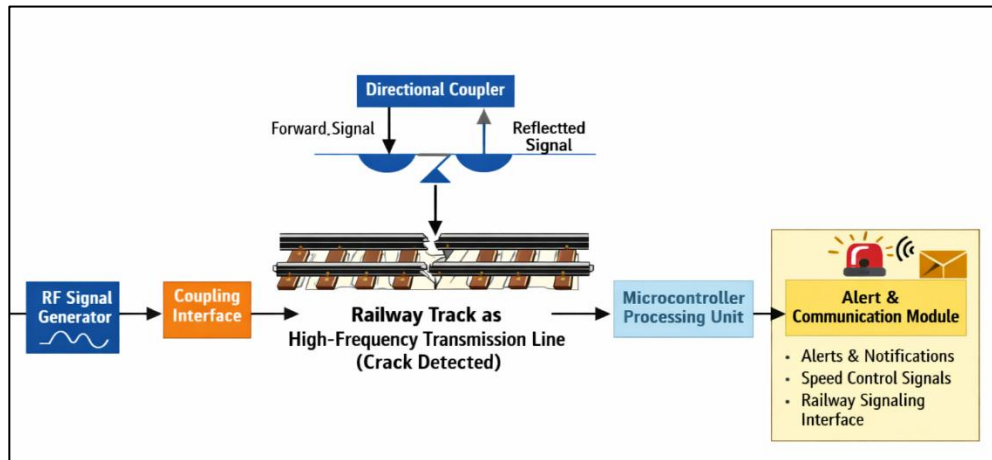


Fig I System Architecture

A continuous RF signal is injected into a predefined rail section through a coupling interface. The directional coupler separates the forward and reflected signals, which are used to compute the VSWR. The processing unit analyses the measured VSWR values and determines the presence of track defects.

4. Principle Of Operation

Under normal operating conditions, the railway track exhibits relatively uniform characteristic impedance, resulting in minimal reflection of the injected RF signal. When a crack or structural defect occurs, it introduces an impedance discontinuity, causing partial reflection of the signal

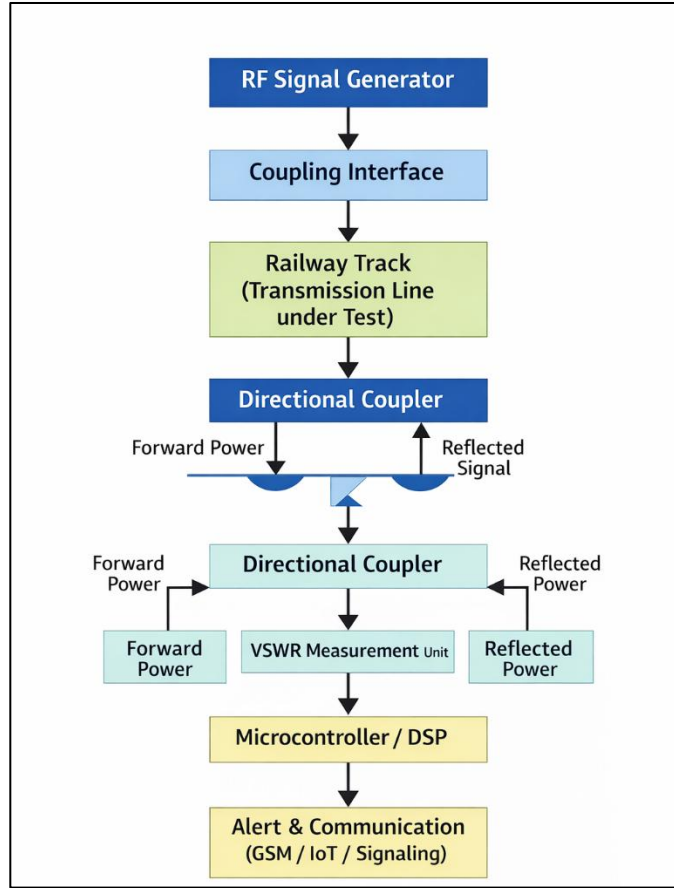


Fig II : System Operation Flow Chart

VSWR is defined as:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

An increase in VSWR beyond a predefined threshold indicates the presence of a defect. By analysing the magnitude and phase of the reflected signal, the approximate location of the fault can also be estimated.

5. Fault Detection and Preventive Action

The microcontroller continuously compares measured VSWR values with predefined safe limits. When the VSWR exceeds the threshold the presence of a crack or defect is confirmed, Alerts are generated via visual indicators, alarms, or wireless communication, Preventive actions such as speed restriction, signal locking, or emergency alerts can be initiated. The system can be integrated with existing railway signalling and control infrastructure for automated response. The proposed railway track monitoring system is based on the principles of high-frequency transmission line theory. In this approach, the railway track is modelled as a distributed transmission line characterized by resistance RRR, inductance LLL, capacitance CCC, and conductance GGG per unit length. A predefined VSWR threshold $VSWR_{th}$ is established based on calibration and empirical testing. Fault detection is performed using the condition:

$$\text{Fault Detected if } VSWR > VSWR_{th}$$

Typical threshold values are selected as:

$$VSWR_{th} \in [1.5, 2.0]$$

The approximate location of the fault can be estimated using time-domain or phase-domain analysis of the reflected signal. If Δt represents the round-trip time delay of the reflected signal and V_p is the propagation velocity along the rail, the distance d to the fault is given by:

$$d = \frac{V_p \Delta t}{2}$$

Where:

$$V_p = \frac{c}{\sqrt{\epsilon}}$$

The microcontroller continuously evaluates the VSWR value:

$$\text{Decision} = \text{Crack Detected when } VSWR > VSWR_{th}$$

“Table I presents representative forward and reflected power measurements obtained under different track conditions. It is observed that VSWR increases significantly with crack severity, validating the effectiveness of the proposed VSWR-based fault detection approach. A threshold value of 1.5 reliably distinguishes healthy and defective rail sections.”

Table I Fault Classification Based on VSWR

Track Condition	Forward Power (W)	Reflected Power (W)	Reflection Coefficient	VSWR
Healthy Track (No crack)	10.0	0.05	0.071	1.15
Minor Surface Crack	10.0	0.20	0.141	1.33
Moderate Crack	10.0	0.60	0.245	1.65
Severe Crack	10.0	1.50	0.387	2.26
Broken Rail	10.0	3.50	0.592	3.90

Table II Fault Classification Based on VSWR

VSWR Range	Track Condition	Recommended Action
1.0 – 1.3	Healthy	Normal operation
1.3 – 1.5	Minor defect	Schedule inspection
1.5 – 2.0	Moderate crack	Speed restriction
> 2.0	Severe crack / break	Immediate stop & alert

Table III Fault Location Estimation

Measured Delay Δt (μ s)	Estimated Distance (m)
2.0	180
3.5	315
5.0	450
7.5	675

Accurate estimation of Voltage Standing Wave Ratio (VSWR) is critical for reliable crack detection in railway tracks, as the decision threshold directly depends on measured reflected and forward power levels. Measurement uncertainty arises from instrumental limitations, environmental conditions, and signal propagation variations along the railway track.

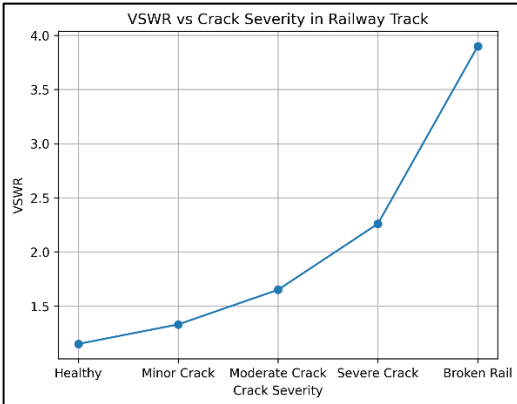


Fig III VSWR vs Crack Severity

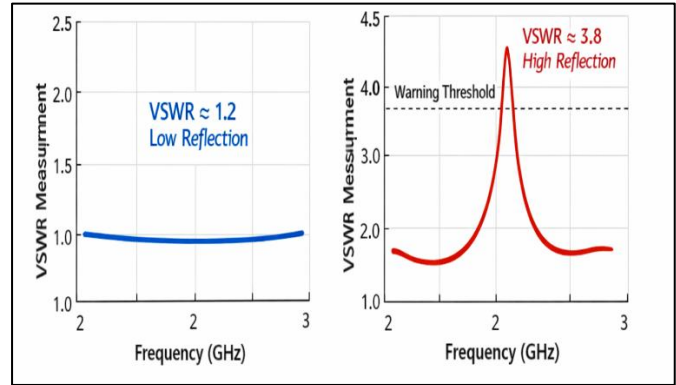


Fig IV Track comparison: Normal vs Faulty using MATLAB

6. Advantages Of The Proposed System

The proposed system enables continuous, real-time monitoring of railway track integrity using a non-invasive VSWR-based approach. It operates automatically with minimal human intervention, reducing reliance on manual inspections. Early detection of impedance discontinuities allows timely fault identification, thereby enhancing operational safety and minimizing derailment risks. The system is scalable for long rail sections and is compatible with existing railway infrastructure and signaling systems.

7. Application Potential And Limitations

The proposed system is applicable to national and regional railways, metro rail networks, freight corridors, and high-speed rail systems. It supports predictive maintenance and smart transportation initiatives. Limitations include RF signal attenuation over very long track sections and the need for periodic calibration under varying environmental conditions. These challenges can be mitigated through modular deployment and adaptive calibration techniques.

8. Conclusion

This paper presents a VSWR-based railway track crack detection and prevention system that leverages high-frequency transmission line principles. By treating railway tracks as transmission lines and monitoring impedance discontinuities through VSWR measurements, the system enables continuous, non-invasive, and real-time detection of structural defects. The proposed approach enhances railway safety, reduces maintenance costs, and supports intelligent infrastructure monitoring. Future work includes large-scale field testing and integration with advanced railway control systems. The experimental results conclusively show that VSWR is a highly effective and sensitive indicator of railway track health. The parameter increases monotonically and significantly with the severity of track damage, from a baseline of ~ 1.15 for a healthy rail to nearly 4.0 for a broken rail. This establishes a strong foundation for developing a VSWR-based diagnostic system. Such a system could transform railway maintenance from a scheduled or reactive model to a condition-based, predictive paradigm, enhancing safety, reliability, and operational efficiency. Future work should focus on validating these results in field environments and developing algorithms to discriminate between fault reflections and other environmental impedance variations.

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Conflict of Interest

The author declares no conflict of interest.

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