

# Novel Coil Transducer Induced Thermoacoustic Detection of Rail Internal Defects towards Intelligent Processing

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**Abstract**—A novel resonant tri-coil transducer is proposed to induce thermoacoustic (TA) signals for detecting rail internal defects. It consists of a ferrite plate-backed tri-coil and its associated circuits, a shielding layer, and a three-dimensional printed enclosure for supporting and securing. General TA detection theory is illustrated to understand how to detect rail internal defects. For achieving electromagnetic (EM) field shaping and focusing, the physical structure of the proposed transducer is optimized. It reduces backward EM fields and interference. Then, an equivalent circuit model between the proposed transducer and the rail is constructed to analyze optimal power transfer efficiency as a function of distance and frequency. To validate the design concept, the proposed transducer is fabricated for inducing TA signals, and experiments are performed. Several engineered rail specimens (UIC-60E) with different types of defects are prepared. The induced TA waves are found to be compressional. With selected features, a support vector machine algorithm-based multinomial classifier model is trained and employed for intelligent processing. Then, the proposed transducer is integrated into the self-designed automatic rail monitoring system. Experimental results show that the self-designed system can achieve an accuracy rate of 96.4%, successfully identifying defects in defect classification. The proposed transducer has low cost in fabrication and maintenance, focused magnetic fields with a large lift-off distance and enhanced acoustic wave intensity. Compared to earlier version of the system, the spacing between the transmitter and the rail has been further increased.

**Index Terms**—Automatic rail monitoring, equivalent circuit model, machine learning, rail internal defect detection, resonant tri-coil transducer, thermoacoustic (TA) technique.

## I. INTRODUCTION

HIGH-speed rail transportation is a critical infrastructure supporting the efficient flow of people and goods between cities [1]. The large daily loads put considerable stress on the railway tracks. Combined with complex and severe weather conditions, the expansion and contraction effects of railway

tracks will occur. Over time aging and fatigue would lead to defects in rails [2]. Defect detection has become a key link in preemptive maintenance, preventing further deterioration of the track, reducing maintenance costs, and extending service life. The timely and efficient detection of rail defects is crucial to the safe and reliable operation of rail transportation.

Metal surface and subsurface inspection techniques rely on magnetic flux leakage [3], radiography, machine vision [4], and eddy current [5]. Internal deeper defect detection mainly utilizes ultrasonic waves as it can travel in the rail. According to the deployment distance between the transmitter/receiver and the rail, ultrasonic-based inspection methods are divided into three groups: contact methods, hybrid methods [6], and non-contact methods. The contact method mainly utilizes the piezoelectric material to generate/sense ultrasonic signals, which serves as one of the earliest forms to assess and examine metal objects for internal defects [7]. A couplant is required to facilitate the smooth transmission of ultrasonic waves from transmitters to receivers through the rail. Meanwhile, it reduces frictions between the transmitter/receiver and the rail. Because of the restriction of the contact method, a non-contact method is usually preferred. By utilizing two interacting magnetic fields, an electromagnetic (EM) acoustic transducer was designed to generate ultrasonic waves in test subject [8]. It doesn't need the couplant. Since high coupling coefficient leads to small lift-off distance, it is easy to touch the rail surface when running at high speed due to vibration. Furthermore, it is difficult to regulate the spacing to the rail because of significant attraction force of the permanent magnet. Moving over the rail is difficult because of drag caused by high frictional forces from the permanent magnet [9]. The utilization of the laser could increase the lift-off distance to generate/pick up acoustic signals due to focused light beam [10]. The photoacoustic source is a high-power laser, and it is expensive. Meantime, the laser of picking up acoustic signals has a low accuracy since it is susceptible to optical interference (such as dust) and vibration. Air-coupled ultrasonic sensors could be also used to generate/sense ultrasonic signals via air and the rail [11]. Due to large acoustic impedance mismatching between air and the rail, the power transfer efficiency (PTE) is relatively low.

In addition to inspection techniques, manual data analyses are currently a standard approach for identifying different types of defects, which is inefficient. The detection accuracy depends largely on the experience of operators [12]. To improve this, the machine learning technique gains increasing attention for the defect classification [13]. A multitask learning framework was integrated for multiple detectors to inspect rail ties and fasteners

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