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INTRODUCTION OF A NOVEL SMART SLEEPER DESIGN FOR RAILWAY TRACK CONDITION MONITORING

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Abstract

Railways commonly use ballasted track systems as their primary infrastructure. Increased track tonnage and service speeds require enhanced track condition monitoring and active maintenance protocols. Modern railway track maintenance involves digital and visual inspection algorithms, which becomes time-consuming and costly with increased track lengths. Real-time condition monitoring of railways is important to determine the possible problems cost-effectively and rapidly. Smart sleepers offer real-time data for continuous monitoring of critical track zones. This paper presents the conceptual development of a novel smart sleeper utilizing embedded accelerometers and strain gauges for railway condition monitoring. The conceptual design and prototype production of the smart sleeper involves the installation of accelerometers with three degrees of freedom placed at the sleeper center and the two rail seats of a B70-type prestressed concrete sleeper. The initial phase of this study involves tests conducted in the laboratory to examine the sensitivity of embedded sensors. Sensors are selected to indicate a substantial acceleration interval due to abrupt, rapid, and gradual roughness variations in the track profile and abrupt lateral variations due to track buckling. An embedded electronic circuit board specially engineered for data acquisition is also a part of the smart sleeper. This paper presents the progress made within the first phase of this research and development project that includes the conceptual development of the smart sleeper and its electronic architecture.

Keywords: railway infrastructure, smart sleepers, condition monitoring, embedded sensors

1 Introduction

Railway track ties, also known as sleepers, support the rails and maintain the track gauge through their attachments to the rails. The heavy freight railway tracks in North America frequently employ wood ties whereas the contemporary passenger railway tracks employ reinforced concrete bi-block or prestressed concrete monoblock sleepers.

Railway tracks are subject to various mechanical and climatic effects due to operational demands and environmental conditions. The increased tonnage on railway tracks due to increased speeds, axle weights, and service frequencies has increased the dynamic forces experienced by railway track superstructure and the substructure that can lead to accelerated track damage and reduced track lifespan. Consequently, railway lines require frequent and thorough maintenance. Today, maintenance methods include digital visual inspection algorithms.

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Visual data collected digitally by vehicles moving at specific speeds along the track is analysed based on predetermined maintenance criteria to identify maintenance needs along the track. However, deploying customized maintenance detection tools and teams to inspect track transition areas to bridges, tunnels, and culverts, as well as track curves and acceleration/deceleration zones near stations, which are likely to require additional maintenance, is costly. The most significant cost in maintaining railway infrastructure is the replacement of rails, followed by the cost of sleeper replacement [1]. Additionally, the ballast layer within which the sleepers supporting the rails are embedded, limits the range of a thorough visual inspection of the sleepers [2]. Studies have shown that many sleepers identified as "inadequate" for removal based on visual inspection can still fulfill their basic functions [3]. Visual inspections on railway lines are conducted at regular intervals. However, the condition of the railway tracks remains unknown in between the inspections and their inspections can be improved by real-time continuous data acquisition through continuous monitoring.

A smart sleeper with special sensors located within is an important tool for continuous monitoring and evaluation of railway track conditions. The ability to conduct real-time monitoring of the railway track will extend the service lives of the sleepers and the track defects that can cause loss of serviceability or derailment will be determined in advance thus preventing loss of life and property. Continuous monitoring of the structural health of the railway lines with "smart sleepers" will allow immediate intervention to potential damages and foresee the accumulating problems. Additionally, it will be possible to make a more effective design by evaluating the effects of the elements more correctly along the critical regions of the railway line. Various studies have been conducted in the field [4-8] and laboratory [9-12] regarding railway condition monitoring. However, there is limited information on the long-term performance of these systems.

The main purpose of this study is to develop a novel product that will be a significant tool for railway track condition monitoring especially along critical railway track zones. One such zone is the track transitions where changing track stiffness and track support conditions as well as changing track temperatures, can occur that can lead to detrimental changes in track plan and profile. Another type of zone would be the train acceleration and deceleration regions near stations. Track curvatures are one other type of critical track zone where heavy track damages are found to occur. These distinctive track zones are potential candidates for inducing high vertical dynamic impact forces on the railway track and track buckling. Expected vertical dynamic impact forces due to many types of track roughness that can develop along track transitions and lateral sway due to track buckling are categorized by acceleration intervals that these roughness types and sway can induce on a sensor. The sensors within the smart sleepers are categorized and chosen according to the frequency intervals that the likely track conditions are expected to induce on the railway track and the rolling stock. Following the development of the "smart sleeper" its effectiveness will be examined through laboratory tests.

2 Sensors and data collection system

2.1 Sensors

The smart sleeper will provide data utilizing four distinct types of sensors which are accelerometers, strain gauges, velostat (Pressure-Sensitive Conductive Sheet), and temperature sensors. Each of these sensors was determined to supply certain information for railway track condition monitoring. Dynamic impact forces acting on railway lines cause variations in the track profile in time. These variations primarily occur along the transition zones to engineering structures supporting the railway track.

One other type of dynamic impact force generator concerning the rolling stock is the wheel flats that occur due to compromised wheel circularity [13-15]. There are also other distinctive regions along the railway track such as the turnouts and the insulated rail joints where significant dynamic impact forces occur. All the track and wheel roughness types that have been seen to occur along railway tracks and the rolling stock wheels generate a wide spectrum of dynamic impact forces that range up to frequencies of multiple kilohertz and dynamic impact forces up to 2 to 8 times the static wheel forces under extreme conditions. In terms of the measured accelerations along the railway tracks, the generated accelerations on the accelerometers under extreme dynamic impact forces have been seen to reach more than 300 g.

In order to gauge the responses of the sleeper to the generated dynamic impact forces, the sleeper is instrumented with a specially selected sensor architecture to measure the accelerations, the strains, the bearing pressures, and the ambient temperature at the time of measurement. To determine the dynamic behaviour of sleepers and railway lines and to monitor impact forces of different magnitudes, the ADXL375 accelerometer has been selected. The sensor has a capacity of 200 g in three axes. This limit was judged to be sufficient to respond to many types of dynamic impacts along the railway track due to track roughness. The dimensions are 25.6×17.7×4.6 mm which is relatively small compared to the sleeper. The second sensor is post-yield strain gauge called YFLA-5-3L. Its strain capacity is 0.20 mm/mm and the sensor dimensions are 12×4 mm. The gauge length is selected as 5 mm which is compatible with the diameter of the prestressing bars. Strain data will be obtained from the prestressing bars to monitor the sleeper condition and to determine the train loads. The third sensor is velostat. Its working principle is that the sheet's electrical resistance decreases under pressure. When it is compressed between two conductive layers, it will become a kind of pressure sensor. It will be utilized between the sleeper and ballast layer to determine whether the sleeper is in contact with the ballast. The dimensions are 280×280×0.1 mm. The fourth sensor is the MCP9808 Temperature Sensor. The effect of the temperature on the sleeper will be observed throughout the sleeper's service life. Its measuring range is -40 °C to +125 °C, and its dimensions are 21×13×2 mm. All sensors are presented in Figure 1.

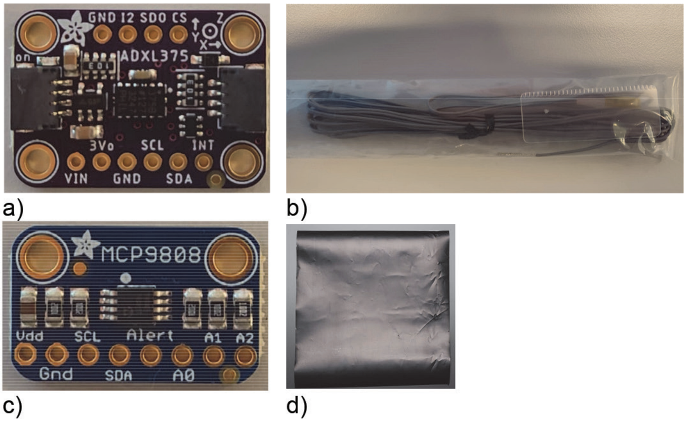

Figure 1 Sensors employed in the smart sleeper: a) Accelerometer; b) Strain gauge; c) Temperature sensor; d) Velostat

2.2 Data collection system

The smart sleeper was intended to monitor multiple sensors and provide data on railway trucks. All sensors are connected to the specially developed smart sleeper board. The board, integrated with the Raspberry Pi card, facilitates data acquisition. Visuals of the plain board before and after the attachment of components are shown in Figure 2.

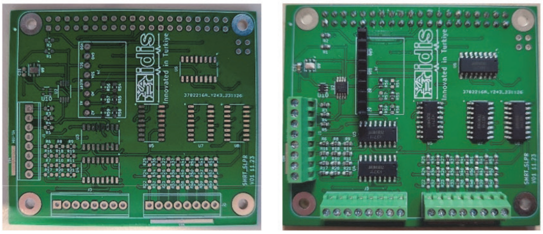

Figure 2 Plain smart sleeper board (left), smart sleeper board with components (right)

Each configuration of the smart sleeper system (conventional and digital) consists of two main structures: An Electrical Protection Block and a Functional Block. Protective equipment was used in the subsystem between wayside equipment for power protection, which provides over-current and over-voltage protection for power lines.

Some of the sensors cannot directly transmit raw data to the controller, thus the data goes to the ADC module first and then is conveyed to the controller via the supported data bus. The designated data path for the strain gauge, accelerometer, velostat, and temperature sensor are UART, SPI, I2C, and I2C, respectively. After the data is interpreted in the control unit, it is transmitted to the SCADA via industrial switches. The system can obtain data from twelve strain gauges, three accelerometers, three velostats, and one temperature sensor.

3 Smart sleeper

3.1 Smart sleeper design concept

The B70 prestressed monoblock concrete sleeper, one of the most utilized sleeper types in the world, was selected for the smart sleeper product. The sensors are located in three different sections, namely two rail seat areas and the centre of the sleeper, since these regions are critical to monitor the sleeper responses to dynamic impact forces.

It was planned to use a total of 12 strain gauges, two for top and two for bottom reinforcements in each of the three sections. In these three sections, there are three accelerometers in the sleeper and three velostats underneath the sleeper. The temperature sensor is located on the smart sleeper board. The data collection card is placed on the upper surface at the edge of the sleeper. A cable channel passing through the sleeper transfers sensor cables to the data collection card. Sensor locations are depicted in Figure 3.

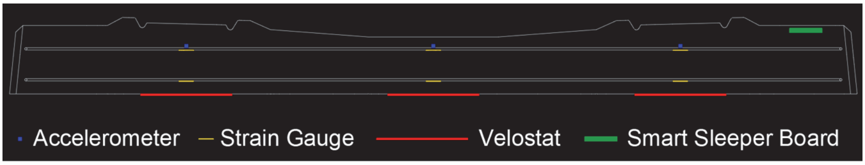

Figure 3 Smart sleeper sensor locations

3.2 Production of prototype smart sleepers

Three prototype smart sleepers have been produced currently. A wooden block having a hole for the cable exit was placed in the sleeper mould for the smart sleeper board location, Figure 4.

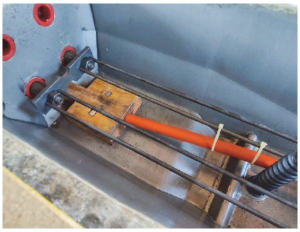

Figure 4 Cable channel (orange color) and wooden block (brown color)

The cable channel was connected to the wooden block and placed in the mould after the sensor cables were placed in it. Cable entrances on the channel were isolated to avoid water leakages. During the production of the third smart sleeper, a plastic junction box was utilized instead of the wooden block to prevent possible cable damage while removing the sleeper from the mould. The three sections where the sensors are located were tagged rail seat 1 (RS1), centre (C), and rail seat 2 (RS2). The rail seat area that is close to the smart sleeper board is referred to as RS2.

The accelerometers were placed in a special formwork and covered with epoxy resin to protect and position them in the sleeper, Figure 5. The epoxy resin prevents the relative vibration of the sensor with respect to the sleeper. The formwork was fastened on a special steel plate placed between two prestressing bars, Figure 5. Thus, the prevention of the movement of the accelerometer ensures that its orientation remains constant.

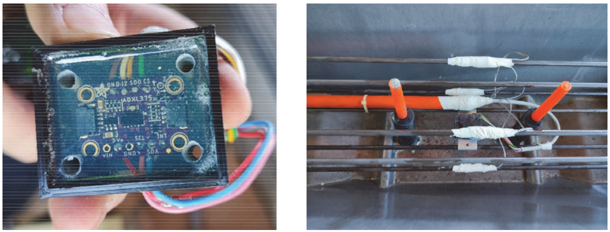

Figure 5 Accelerometer embedded in epoxy resin (left) and sensor locations at rail seat area 'RS1' (right)

Strain gauges were attached to the prestressing bars and wrapped with insulating tape, Figure 5. Although six and nine strain gauges were attached to the top and bottom bars, respectively, the smart sleeper board can receive data from the twelve strain gauges. The remaining three strain gauges will be utilized to validate the data obtained from the smart sleeper board.

Figure 6 shows the production phase of the smart sleepers. The first sleeper includes fifteen strain gauges, three accelerometers, and one temperature sensor. The second and third prototype sleepers have two accelerometers, and the third sleeper has nine strain gauges. Velostat sheets will be placed in their locations at the laboratory. The numbers of each type of sensor will be optimized after the tests that will be conducted by using the hydraulic actuators.

Figure 6 Smart and ordinary sleepers before and after concrete pouring

3.3 Preliminary test

A preliminary loading test was performed on one of the prototype smart sleepers. The heavy steel blocks were placed at the centre section of the sleeper to examine the response of the strain gauges to the gradual load increments, Figure 7. Consistent with expectations, an increase in the load corresponded to an increase in deformation at the sleeper's bottom section and a decrease in deformation at the top section at the sleeper centre cross-section. The recorded mass-strain graphs are presented in Figure 7. It can be seen that a linear behaviour was observed at the loading part. After the weights were removed, there were some residual deformations at each strain gauge. The variance between the loading and unloading paths and the residual strains might be clarified in the tests in which hydraulic actuators are utilized. After compiling the preliminary tests for the other sensors, variable amplitude and frequency tests will be conducted by using the hydraulic actuators.

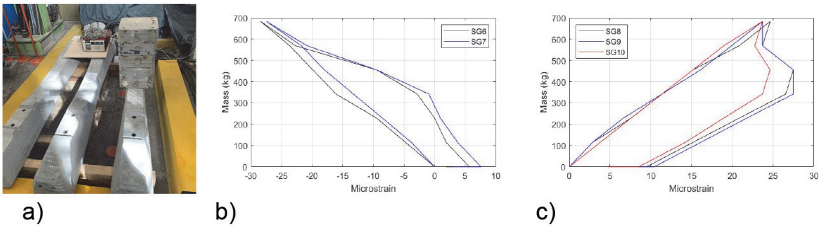

Figure 7 Preliminary loading test: a) Test setup; b) Strain at the top section; c) Strain at the bottom section

4 Conclusions

The development of the smart sleeper represents a significant advancement in railway track condition monitoring. By integrating multiple sensors into the sleeper, including accelerometers, strain gauges, velostats, and a temperature sensor, a comprehensive understanding of the dynamic behaviour and condition monitoring of railway tracks can be achieved. This continuous monitoring allows for the early detection of potential issues, enabling timely maintenance interventions and ultimately enhancing the safety and longevity of railway infrastructure. Prototype smart sleepers have been produced and the early preliminary test has shown promising results. The future work includes various testing and optimization of the smart sleeper design for practical implementation in railway maintenance practices.

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