Enhancing Railway Safety through Remote Monitoring of Railway Expansion Switches Using Linear Sensors in Continuous Welded Rail

Laboratory evaluation of pull wire and acoustic sensors with Ansys finite element comparison

Nicholas Riches

School of Architecture, Computing and Engineering, University of Sunderland, Sunderland, United Kingdom

Abstract: ***This study examines how two types of simple linear sensors- a pull wire and a short-range acoustic sensor can monitor the movement of expansion switches in continuous welded rail. A full-scale lab setup was used to test how well these sensors measure rail overlap and gap under different temperature settings. Their readings were compared against benchmark values and thermal displacement estimates from both a basic expansion formula and Ansys finite element models. Results show that both sensors worked well within a practical temperature range, with small errors. At higher temperatures, the pull wire sensor showed slightly more deviation. The findings support the idea that these low-cost sensors could play a key role in ongoing rail safety monitoring, though further field tests are needed.***

Keywords: rail expansion switch, structural health monitoring, pull wire sensor, acoustic sensor, thermal displacement

1. Introduction

Continuous welded rail reduces impact loading and improves ride quality by eliminating joints, but it introduces sensitivity to thermal loading and constrained expansion. If the rail temperature rises above the stress free temperature without sufficient lateral resistance, compressive forces may lead to lateral buckling. Expansion switches are installed to accommodate longitudinal movement at locations where rail stress cannot be fully managed by conventional stress adjustment and anchoring. In current practice, inspection of expansion switches relies on manual measurement of switch rail overlap and gap opening at defined temperature bands. This approach is periodic and labour intensive, and it cannot track shifting patterns or quick temperature effects as they happen between inspection intervals.

This paper evaluates two low complexity linear sensor systems for monitoring expansion switch movement. The objective is to determine whether pull wire and acoustic sensors can measure overlap and gap opening accurately enough to support regular safety monitoring and remote condition assessment. Numerical thermal expansion theory and Ansys finite element analysis are included to provide a reference behaviour and to support interpretation of sensor outputs.

Background and need for monitoring

Rail stress management remains a core safety issue in modern railways, with established approaches including stress free temperature measurement and risk-based evaluation of buckling hazards. Remote monitoring offers a route to earlier detection of abnormal movement patterns and improved targeting of maintenance interventions. Structural health monitoring frameworks emphasise the value of repeated measurements linked to performance indicators and failure modes, rather than isolated measurements taken at long intervals.

2. Methodology

A. Research design

A mixed methods approach was used, combining an industry survey, laboratory testing of sensor systems, and comparison with numerical and finite element thermal expansion models. The primary focus of this paper is the laboratory and modelling components, with the survey used to contextualise industry needs and constraints.

B. Laboratory mock up, instrumentation and procedure

A laboratory mock up of an expansion switch was constructed with a maximum overlap dimension of approximately 760 mm. Displacement was simulated using controlled movement of the switch rail, with temperature points represented by calibrated setpoints aligned to standard guidance. Two sensor systems were evaluated. The first was a draw wire encoder (pull wire sensor) installed to measure linear displacement. The second was a short range acoustic sensor (LogIT Ranger VS) configured to measure distance to a target plate. Both sensors were connected to a LogIT data logger and data acquisition software (SensorLab) for logging and export. Calibration was carried out at each temperature point before recording overlap and gap readings.

Accuracy assessment followed a pragmatic approach using tolerance checks based on the rule that instrument resolution should be 10 times finer than the variation range, to ensure that measurement resolution is adequate relative to the tolerance band. Errors were calculated by comparing sensor measurements with target setpoints for overlap and gap opening.

C. Numerical and finite element modelling

A numerical estimate of longitudinal thermal expansion was calculated using the linear expansion relationship, $\Delta L = \alpha L \Delta T$, where α is the coefficient of thermal expansion for rail steel, L is the rail length, and ΔT is the temperature change. The coefficient α was taken as 15×10^{-6} per deg C. The representative length for scaling was 320 m, consistent with a long continuous welded rail segment.

A finite element model was created in Ansys Mechanical (Release 2023 R1) using a rail profile (FB 113A). The model used a 5 mm element size. The mesh included 25,956 elements and 32,045 nodes. Boundary conditions included a fixed support at the base and an axial head force of 50 kN. Thermal conditions were applied for temperatures of 0, 5, 10, 15, 20, and 30 deg C. Output displacement values were extracted for comparison with the numerical model, since finite element results vary based on how constraints and base settings are applied.

3. Results

A. Benchmark expansion switch settings

Benchmark overlap and gap opening settings for expansion switches were taken from Transport for London Track handbook 6: Prevention of buckling (TfL Management System, Doc. No. G3206, Issue A1, 2014) [1]. Table 1 summarises the specified overlap and gap opening values across rail temperature bands.

Table 1: Benchmark overlap and gap opening versus rail temperature [1]

Rail temperature (°C)	Overlap of switch rails (mm)	Gap opening (mm)
−4 to +2	635	125
3 to 7	641	119
8 to 13	648	112
14 to 18	654	106
19 to 27	660	100

The benchmark shows increasing overlap and decreasing gap with rising temperature, consistent with thermal expansion behaviour and the requirement to maintain safe geometry across the operational temperature range [1].

B. Laboratory calibration setpoints

For the laboratory programme, mean calibration setpoints were defined for nominal temperature points of 0, 5, 10, 15, 20, and 30 deg C. The 30 deg C point was included as an extended condition to explore sensor behaviour at high displacement. Table 2 presents the target overlap and gap values used in the calibration process.

Table 2: Laboratory calibration setpoints for overlap and gap

Temperature (deg C)	Target overlap B (mm)	Target gap A (mm)
0	635	125
5	641	119
10	648	112
15	654	106
20	665	95
30	749	21

C. Sensor measurement results and error

Table 3 compares pull wire and acoustic sensor measurements against the calibration setpoints. The maximum absolute error at each temperature point is reported as the larger of the overlap and gap absolute deviations.

Table 3: Sensor measurements and maximum absolute error at each calibration point

Temp (deg C)	Pull wire overlap (mm)	Pull wire gap (mm)	Pull wire max abs error (mm)	Acoustic overlap (mm)	Acoustic gap (mm)	Acoustic max abs error (mm)
0	635	125	0	633	127	2
5	638	122	3	640	120	1
10	647	113	1	645	115	3
15	652	104	2	652	108	2
20	664	96	1	666	94	1
30	742	18	7	751	23	2

Across the calibration points up to 20 deg C, both sensors produced maximum absolute errors at or below 3 mm. At 30 deg C, the pull wire sensor showed a larger overlap deviation, resulting in a maximum error of 7 mm, while the acoustic sensor remained within 2 mm.

Fig. 1 summarises the maximum absolute error trend for each sensor across the calibration points.

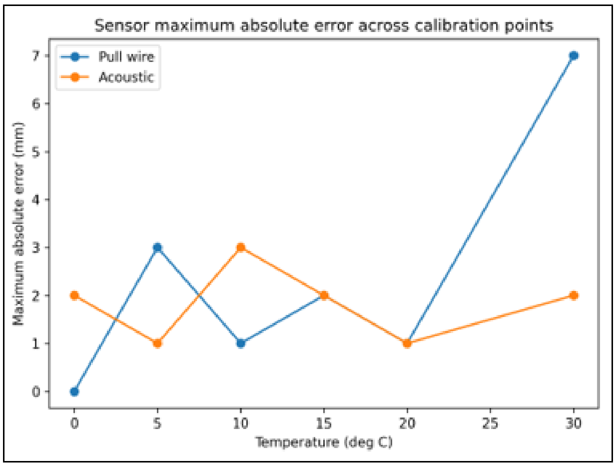

Figure 1: Maximum absolute error for pull wire and acoustic sensors across calibration points

D. Numerical and finite element thermal expansion results

Table 4 presents longitudinal thermal expansion estimates from the numerical model and Ansys finite element analysis for temperature points between 0 and 30 deg C. The numerical model predicts a linear increase in ΔL with temperature, while the finite element outputs reflect the influence of boundary conditions and reference definitions within the model.

Table 4: Numerical and Ansys finite element thermal expansion outputs

Temp (deg C)	Numerical ΔL (mm)	Temp (deg C)	Ansys (FEA) ΔL (mm)
0	0	0	84.42
5	24	5	65.5
10	48	10	46.7
15	72	15	27.9
20	96	20	9.86
30	144	30	29.09

Fig. 2 plots the numerical and Ansys results from Table 4. The numerical model increases linearly as expected for uniform thermal loading. The finite element results show a decreasing displacement magnitude between 0 and 20 deg C and a rise at 30 deg C, which is discussed in relation to modelling assumptions and constraints in Section IV.

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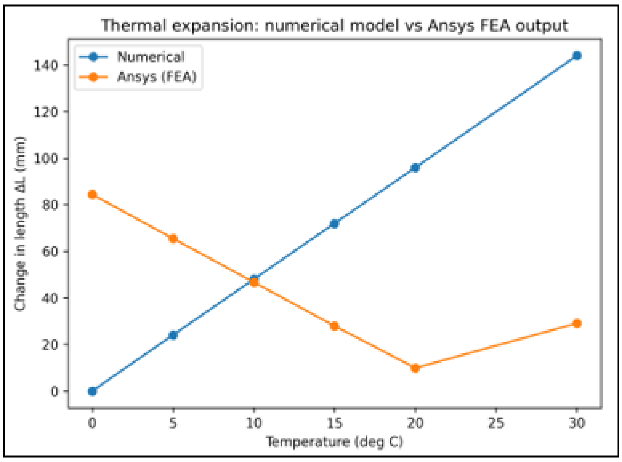

Figure 2: Thermal expansion behaviour from numerical model and Ansys FEA output

E. Industry survey summary

An industry survey was distributed through professional networking groups to assess current practice and appetite for remote monitoring of rail stress and expansion switch behaviour. The survey received 3,185 views and 72 responses, with seven excluded due to incomplete or low quality entries. The final dataset comprised 65 completed responses from six countries across four railway disciplines. Qualitative themes indicated demand for continuous measurement systems, improved access for maintenance, clearer data capture tools, investment in reliable technology for validation, and improved staff training in prevention of buckling principles.

4. Discussion

The laboratory results indicate that both pull wire and acoustic sensors can capture expansion switch geometry with small errors relative to the target settings. Within the standard temperature range represented by the 0 to 20 deg C calibration points, the maximum absolute errors were limited to 3 mm or less, suggesting suitability for detection of gradual drift and abnormal movement patterns. The extended 30 deg C point highlighted potential sensitivity of the pull wire arrangement to installation geometry, sensor range, or alignment at high displacement, while the acoustic sensor remained stable within a 2 mm error. This supports the use of redundancy or hybrid measurement approaches in field deployment where environmental influences may be stronger.

The numerical thermal expansion model provides a simple reference behaviour, but it does not represent track constraint, ballast resistance, or stress redistribution. The Ansys outputs differ from the numerical values, which is attributed to model boundary conditions, the application of axial force, and reference temperature definitions. Finite element modelling remains valuable for sensitivity exploration, but field calibration is required before using finite element displacement magnitudes directly for decision making.

The survey results align with the laboratory findings in indicating that the industry values real-time data and clearer insights. Any practical deployment should integrate sensor outputs with asset management systems, define alarm thresholds based on standards such as G3206, and include governance for data integrity and maintenance response.

5. Conclusion

This study assessed two linear sensor systems for monitoring expansion switch overlap and gap opening in continuous welded rail. Laboratory testing showed that both pull wire and acoustic sensors can measure displacement with small errors across representative temperature points. The acoustic sensor provided consistent performance at the extended 30 deg C condition, while the pull wire sensor showed a larger deviation at this point, indicating the need for installation optimisation and range management. Numerical and finite element modelling supported interpretation of longitudinal movement and provided a basis for further modelling development. The findings support continued development and field validation of low complexity remote monitoring solutions for expansion switch structural health monitoring and rail stress management.

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