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# Experimental Analysis of Flat Spot-Induced Vibrations Using Piezoelectric IEPE-Accelerometers

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## Summary:

This work presents an experimental approach to investigate and classify material vibrations induced by flat spots on train wheels. The simplified test setup intentionally omits spring elements, while vibration data is acquired using integrated electronics piezo-electric (IEPE) accelerometers. Both time-domain and frequency-domain analyses are applied to comprehensively evaluate the vibrational behaviour. The results offer valuable insights into the dynamic effects of flat spots, paving the way for implementing diagnostic sensor networks in railway systems.

**Keywords:** Railway, Flat Spot, IEPE Accelerometers, Vibration Analysis, Predictive Maintenance

## Introduction

Railway maintenance is increasingly shifting from time- and usage-based strategies toward condition monitoring and predictive maintenance. In predictive maintenance, accurate data analysis is crucial for estimating a component's lifespan, making it essential to classify and investigate critical failure modes [1]. One such failure mode is the development of flat spots on train wheels. These flat spots result from wheel wear caused, for example, by emergency braking or delayed brake release during acceleration and generate periodic impact forces during rotation, ultimately damaging both the wheel and the infrastructure. [2]. In addition to the detection of flat spots, a well-designed sensor network also enables the monitoring of relevant environmental factors, which can be of decisive importance for the precise estimation of component service life. Our approach aims to improve fault diagnosis and contribute to more effective predictive maintenance strategies in railway operations.

## Experimental Details and Theory

To investigate wheel-induced excitations under controlled conditions, a scaled test rig equipped with IEPE-accelerometers was designed specifically for detecting flat spots on train wheels. To ensure a realistic representation of the railway system, a scale conversion of approximately 1:4.6 was determined based on the ratio between an actual railway wheel and the acquired flange rollers. The experimental setup includes four rail flange rollers, that are rigidly connected via a steel plate and run on rails without any additional suspension or damping elements. This direct, rigid coupling ensures that any impulsive excitation - such as that produced by a flat spot on a wheel - is transmitted almost immediately and uniformly to the entire system. A USB-Signal Conditioner is recognized as a microphone, enabling straightforward data logging with just a few lines of code. Four predefined measurement positions mounts (denoted as $\mathrm{M_n}$) are distributed along the structure to allow comparison of vibration responses between the different wheels. When a flat spot contacts the rail, it generates a transient impulsive force $F(t)$, which results in a measurable acceleration response along the vertical z-axis [3]. The coordinate system and sensor positions on the model are illustrated in Figure 1.

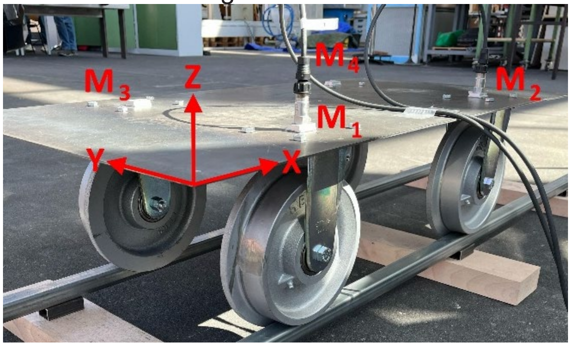

*Fig. 1. Experimental Setup*

Assuming that the system behaves like a single-degree-of-freedom damped oscillator, the dynamic response shown in figure 2 is described by the equation of motion (1) [4].

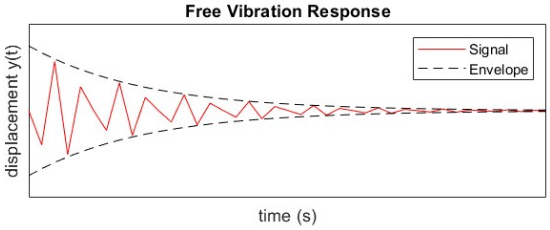

*Fig. 2. Damped sinusoidal oscillation*

$$F(t) = m\ddot{y}(t) + c\dot{y}(t) + ky(t) \qquad (1)$$

Where $m$ is the effective mass of the system, $c$ is the damping coefficient, $k$ is the effective stiffness of the rigid connection and $y(t)$ represents the displacement response. Equation (2) gives the free vibration response (assuming underdamped conditions, $0 < \zeta < 10$) for the case where the impulsive force can be approximated as an instantaneous excitation.

$$y(t) = Ae^{-\zeta\omega_n t}sin(\omega_d t + \phi) \qquad (2)$$

$A$ being the initial amplitude determined by the impulse magnitude, $\zeta$ the damping factor, $w_n$ the natural frequency, $w_d$ the damped natural frequency, and $\phi$ a phase constant determined by the initial conditions [4].

## Results and Discussion

Figure 3 illustrates a one-shot measurement of the flat spot hitting the rail while comparing two measuring points $M_1$ and $M_2$. Overall, the measurement confirms the theory of a damped sine wave with its decaying oscillatory behaviour. For better comparison we added envelope curves in both figures 2 and 3.

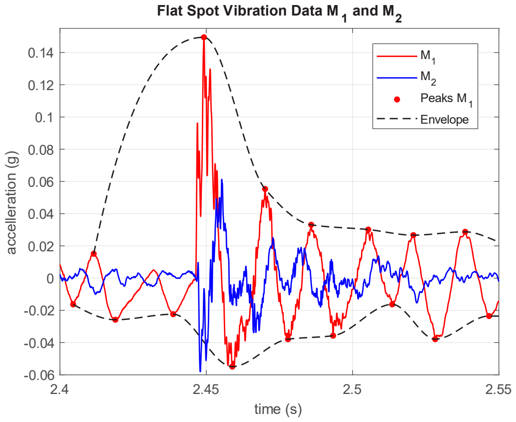

*Fig. 3. Comparison of theoretical and measured flat spot signals.*

While $M_1$ gets the higher peak values, because its sensor is placed directly over the wheel with the flat spot, placing $M_2$ over one of the rear wheels results in a more damped and phase shifted response of $M_1$. This implies that, based on the system's damping characteristics and the materials and weight distribution used, the sensor node for detecting flat spots can be placed farther from the excitation source. The temporal shift of the signal peaks suggests that a simple time-of-flight analysis could be sufficient to determine the exact location of the flat spot. However, when sensors are installed on both axle A and axle B, there is a risk that the flat spot signal may be detected at the alternate location. This makes it crucial - especially for pattern recognition and peak detection - to develop a sensor network that can unambiguously determine the origin of each flat spot. The frequency analysis of the measurement data shows that the dominant vibration modes lie in a clearly defined frequency range between 20 Hz and 100 Hz.

## Conclusion and Outlook

This study demonstrates the feasibility of using piezoelectric accelerometers in a scaled test setup to detect flat spots on train wheels. The setup replicates the impulsive excitations from wheel defects and allows analysis of vibration responses across multiple sensor positions, confirming the behaviour of a damped single-degree-of-freedom system and providing insights into spatial excitation propagation. In future, the system will be optimized with a custom sensor network for both flat spot detection and continuous environmental monitoring to more precisely assess external influences on service life. Additionally, a motor-driven test rig is under development to enable controlled wheel rotation, facilitating the analysis of periodic impact responses at varying speeds. This will help to better understand the frequency content of flat spot signatures and the influence of speed, ultimately supporting the design of robust, speed-invariant detection algorithms for real-world predictive maintenance in railway systems.

## References

[1] A. Murtaza, A. Saher, M. Zafar,S. Moosavi, M. Aftab, Paradigm shift for predictive maintenance and condition monitoring from Industry 4.0 to Industry 5.0: A systematic review, challenges and case study, *Results in Engineering* Volume 24, https://doi.org/10.1016/j.rineng.2024.102935

[2] L. Pan, B. Lu, C. Yang, L. Chen, Y. Song, T. Zhang, The Impact of Wheel Flat on Traction Drive System of Electric Locomotives*, IET Electrical Systems in Transportation* Volume 2024, Issue 1, doi: 10.1049/2024/2889871

[3] A. Sharma, V. R. Reddy, "Wireless sensor networks for condition monitoring in the railway industry: A review," *Sensors*, vol. 20, no. 21, p. 6239, Oct. 2020

[4] C.M. Harris, A.G. Piersol, *Harris' Shock and Vibration Handbook*, 5th ed. (McGraw-Hill, New York, 2002); doi: 10.1121/1.397223