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METHODS FOR TRACK STIFFNESS MEASUREMENT - STATE OF THE ART*

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Abstract*: Track stiffness is a parameter which significantly influences to the track geometry deterioration, rail fatigue and deterioration of other superstructure and substructure components during the track service life. Track stiffness measurement has great theoretical and practical importance for the design of new railway lines, as well as for upgrade and maintenance of existing railway lines. This paper analyses standstill and continuous measurement methods for static and dynamic track stiffness, which are used worldwide. In addition, it presents measurement principles and performances used for inspection vehicles and devices, and guidelines for selection of the optimal method for stiffness measurement depending on the user requirements.*

Keywords: *railway, track, stiffness, measurement methods*

1. INTRODUCTION

Track stiffness is the significant parameter from the aspect of designing, construction and maintenance of the railway superstructure and substructure. During the life cycle of the track, track stiffness significantly influences track geometry deterioration, rail fatigue, and deterioration of the other components of the railway superstructure (Puzavac et al., 2012).

The total track stiffness reflects the stiffness characteristics of the whole track structure. In general, the track stiffness measurement relates to the measurement of total track stiffness (Wang et al., 2016). The stiffness of single track components (for example rail fastening) can be measured in laboratory conditions, while the stiffness of the track foundation can be measured using field test methods or laboratory testing (for example soil samples) (INNOTRACK, 2006).

The modern definition of stiffness implies inelastic and nonlinear behaviour of the superstructure and substructure components, as well as the difference between the stiffness under static and under dynamic load (Puzavac et al., 2012).

Quasi-static and dynamic vehicle excitations lead to ground-borne vibrations. The quasi-static excitation is determined by the static component of the wheel loads, axle distances and vehicle speed. On the other hand, the dynamic excitation is induced by wheel, rail and track geometry irregularities, as well as by uneven track stiffness along the track (Nielsen et al., 2013; Popović and Radović, 2013).

The dynamic wheel–rail contact forces are an important source to ground-borne vibrations and noise, which are generated by irregularities in track geometry, uneven track stiffness along the track (transition zones, hanging sleepers, culverts, etc), and/or wheel out-of-roundness (Nielsen et al., 2013; Popović et al., 2015). Therefore, in order to efficiently

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control ground-borne vibrations and perform optimal maintenance, it is necessary to use accurate measurement systems (Nielsen et al., 2013).

There are different vehicles and devices for standstill and continuous track stiffness measurements. The standstill track stiffness measurements are carried out using a quasi-static or dynamic axial load. The result of this kind of measurement is the load-deflection diagram, which could be used for stiffness assessment. While standstill measurements are more often used for research purposes, continuous measurements are used for maintenance purposes. The most existing methods imply measurement of the displacement in the vertical plane due to the wheel or axle load (Hosseingholian et al., 2009).

However, comparison of the results obtained using two or more methods on the same track section would show different vertical track stiffnesses. Different results could occur due to different: static preloads, excitation frequencies and vehicle speed, spatial resolutions, model dependency and degree of influence from track geometry irregularities (Hosseingholian et al., 2009; INNOTRACK, 2006; Nielsen et al., 2013).

2. STANDSTILL METHODS FOR TRACK STIFFNESS MEASUREMENT

The standstill measurement of total track stiffness implies that a measurement point is defined in advance. Hence, total track stiffness could be calculated by measuring displacement due to the vertical force (Wang et al., 2016).

The total track stiffness could be measured using the following methods: traditional hydraulic jack-loading method, impact hammer method, FWD (falling weight deflectometer) method, TLV (track loading vehicle) method, "PANDA" method, as well as using different types of sensors (devices) - strain gauges, accelerometers, displacement transducers, etc (INNOTRACK, 2006; Wang et al., 2016).

Traditional hydraulic jack-loading method applies a certain force on the rail while measuring the rail deflection with a displacement meter, thus providing the load-deflection diagram (Figure 1). The total track stiffness could be calculated according to definition of secant or tangent stiffness (Puzavac et al., 2012; Wang et al., 2016).

Figure 1. Traditional hydraulic jack-loading and displacement meter (Wang et al., 2016)

Impact hammer method measures track vibrations with accelerometers installed on rails or sleepers. Track vibrations are induced using an impact hammer as an impulse load (Figure 2, left). The receptance could be determined by double integration of the vibration diagram (Berggren, 2009). The impact hammer method covers frequency interval between 50 Hz and 1,500 Hz, which depends on the material of the hammer head. A soft-rubber hammer head is suitable for lower frequencies than a hardmetal one. The impact hammer method is not reliable for the frequencies less than 50 Hz (Wang et al., 2016).

Although FWD (Falling Weight Deflectometer) is used for standstill measurements of total track stiffness, measurements are performed quickly and easily. FWD principle implies weight that falls on the sleeper and simultaneous measurement of the sleeper vibrations. The standard FWD method uses a 125 kN weight which falls onto the sleeper from known height. The vibrational response is generally measured with velocity transducers or geophones (Berggren, 2009; INNOTRACK, 2006; Wang et al., 2016).

TLV (Track Loading Vehicle) uses its own weight as track load, which is transferred using hydraulic jacks. Comparing to the traditional hydraulic jack-loading method, this method is easier to perform and could provide a larger vertical force. The Swedish TLV weights 49 t and could statically load rail up to 150 kN and dynamically up to 200 Hz (Figure 2, right). The main advantage of TLV for standstill measurement compared to the rolling measurement is that preload, dynamic load and frequency range might vary to a greater extent. However, the measurement process is more time consuming and demands track closure (Berggren, 2009; Wang et al., 2016).

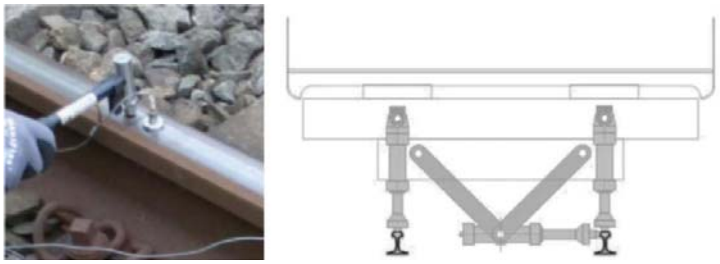

Figure 2. Impact hammer method (left) and the Swedish TLV (right) (Wang et al., 2016)

Penetration testing (static or dynamic) is mostly used. Penetrometer called "PANDA" has been used for determination of the local track stiffness. This penetrometer determines the resistance of the track structure layers to the penetration of the cone (Figure 3). Using field measurements with "PANDA" in combination with endoscopy, different layers of track structure could be indentified, as well as layer thickness and cone penetration resistance (INNOTRACK, 2006).

In addition, track deflection could be measured by following methods: particle image velocimetry or digital image correlation, as well as different conventional sensors, optical sensors, geophones, MDD (multi-depth deflectometers) shown in Figure 4 (left) and LVDT (linear variable differential transformers) shown in Figure 4 (right) (Kouroussis et al., 2015).

Although measurements using strain gauges were considered as the most accurate methods to detect the dynamic load and train speed, their application have certain disadvantages (electromagnetic interference, fragility, excessive size, and high dependence on the temperature). MPQY (Multi-Purpose Q and Y load detector), which consist of strain gauges directly attached to an intermediary device, could be placed on the rail web and provide the possibility of simultaneous measurement of the vertical, lateral and longitudinal forces acting on the rail (Figure 5, left). Modern sensors are efficiently applied in monitoring of various engineering constructions. Their advantages are high temperature capacity, multiplexing, insensitivity to the electromagnetic interferences (Kouroussis et al., 2015).

Figure 3. "PANDA" penetrometer (http://www.macben.be/s9-draagkracht/?lang=en, 28.06.2017) and identification of track structure layers using endoscopy (http://bsh-muc.com, 28.06.2017)

Figure 4. MDD (left) and LVDT (right) devices (https://www.slideshare.net/RailwaysandHarbours/rail-deflection, 28.06.2017)

Different types of motion transducers are used for track deflection measurements. Although displacement transducers contribute only to the measurement of relative displacement, accelerometers represent the most commonly used types of absolute displacement transducers due to their simple mounting, as well as their large dynamic and frequency ranges. In addition, geophones (seismic sensors) could be used due to their advantages, such as the ability to measure large displacement amplitudes, easy power supply, low cost, etc. On the other hand, laser Doppler velocimetry and high-speed video camera could be used to determine the rail deflection. However, these two methods cost relatively much, comparing to geophones (Nielsen et al., 2013).

The usage of accelerometers in combination with adequate signal processing offers an efficient alternative to continuous displacement measurements. Modern accelerometers such as MEMS (micro electro-mechanical systems) are interesting and economically viable transducers, which could be bundled together with other sensors (inclinometers, strain gauges, distance sensors) into compact systems for cost-effective monitoring of railway infrastructure using wireless networks (Nielsen et al., 2013).

Direct measurement of rail deflection using laser beam sensors and indirect measurement of rail deflection using geophone were conducted on the high speed line Madrid-Barcelona, as it was described in (INNOTRACK, 2006). The laser beam receiver and the geophone were clamped to the rail foot next to each other (Figure 5, right). After the signal processing, it was determined that the maximum displacement amplitudes measured by the geophones corresponded to the amplitudes obtained by the laser system.

Figure 5. MPQY detector (left) (Molatefi and Mozafari, 2013) and mounted laser beam receiver and geophone (right) (INNOTRACK, 2006)

3. CONTINUOUS METHODS FOR TRACK STIFFNESS MEASUREMENT

Standstill methods are used for measurements on the level of track section, and continuous methods are used for measurements on the level of railway network.

China Academy of Railway Sciences (CARS) was among the first to develop a vehicle for the continuous measurement of static stiffness. The measurement vehicle consists of one heavy and one light car at the end of the vehicle. The axle load of the heavy car could be changed by adjusting the number of concrete blocks up to a maximum of 250 kN. Accordingly, the impact of different axle loads on the measured results could be obtained. The light car weights 40 kN and it is used to reduce the influence of the track geometry irregularities on the stiffness measurements. The vehicle travels at speeds up to 60 km/h and measures the track geometry using the chord method. The deflection measured under the lower load represents the track geometry irregularity, and the difference between measured deflections under the high and low load represents the track flexibility. More details about this vehicle are provided in (INNOTRACK, 2006; Wang et al., 2016).

Transportation Technology Center, Inc. in Pueblo, Colorado (TTCI) has developed a track loading vehicle for measurements of lateral and vertical static stiffness at standstill measurements, as well as at speed up to 16 km/h. The measurement principle is based on the chord method, where different axial loads are used in order to make the difference between the track geometry irregularity and the track deflection. As shown in Figure 6, this vehicle consists of heavy car, light car and towing locomotive. The heavy car has a central (fifth) wheelset, which could be loaded hydraulically (vertically and laterally) between 4 kN and 267 kN. The stiffness is measured under the load up to 44 kN or 178 kN, and the track geometry irregularity is measured under the load up to 8.9 kN. Under the load of 178 kN, the displacement measurement includes track and subgrade, while the measurement under the load of 44 kN includes rails, sleepers and ballast (INNOTRACK, 2006; Wang et al., 2016).

The vehicle speed for continuous static stiffness measurement developed by the Swiss Federal Railways (SBB) ranges from 10-15 km/h (Figure 7, left). The measurement method consists in measuring the relative track deflection between light and heavy cars. Track deflection under the light car could be considered as negligible due to the very low axle load. The axle load of heavy car is 20 t. Measurements are usually not used to detect hanging sleepers, but there are investigations of the longer wavelength irregularities resulting from variations of soil properties, at bridges, and due to the influence of the USP (Under Sleeper Pads), etc (Nielsen et al., 2013). More details about described vehicle are presented in (Nielsen et al., 2013; Wang et al., 2016).

Figure 6. TTCI vehicle for track stiffness measurements (http://www.drgw.net/trips/report.php?tr=TTCI.3, 28.06.2017)

The company M-Rail commercialised the method developed by the University of Nebraska at Lincoln (UNL) in USA (Figure 7, right). The measurement vehicle uses two laser sources mounted on the bogie, which measure the relative rail deflection. The measurement principle is shown in Figure 8. The relative deflection is measured using two lasers and camera that measures the distance (d) between two laser lines. As the sensor moves closer or further from the rail surface, the distance between laser lines changes. The relation between the measured deflection and track stiffness is based on the Winkler foundation model (INNOTRACK, 2006; Nielsen et al., 2013; Wang et al., 2016).

Figure 7. SBB vehicle for track stiffness measurements (left) (Nielsen et al., 2013; Wang et al., 2016) and mounting position of the UNL measurement system (right) (Wang et al., 2016)

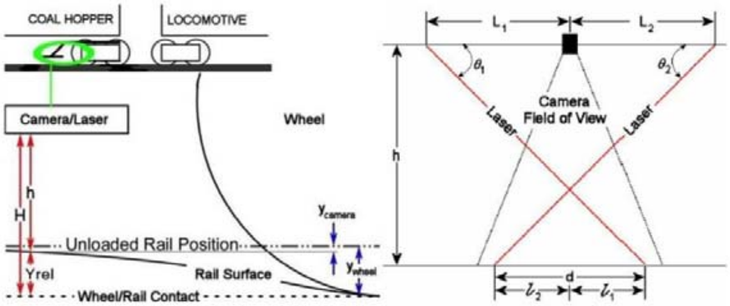

Figure 8. Schematic view of the UNL measuring system (Berggren, 2009; Greisen, 2010)

ZOYON Technology Co., Ltd of Wuhan University and Delft University of Technology developed the method based on measuring of the deformation rate for the purpose of its application in stiffness measurement vehicles. According to this method, the ratio of the vertical track deflection rate at a point and the load moving rate along the railway line determines the slope of track deflection line at that point (Figure 9). High-speed deflectograph was used for measurements of the track deflection rate. The measuring principle is based on several laser Doppler sensors mounted to a railway vehicle which could travel at speed up to 130 km/h. However, this method for static stiffness measurement has limited application since it does not take into account the influence of the track geometry irregularity (Wang et al., 2016).

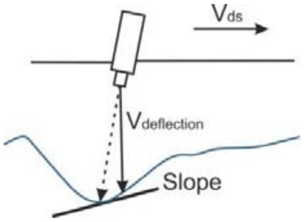

Figure 9. The measurment principle of ZOYON method (Wang et al., 2016)

The aim of Eurobalt II (EUropean Research for an Optimised BALlasted Track) project, which was conducted by Swedish Railways Administration (Banverket), was development of the trolley for continuous measurement of quasi-static and dynamic vertical track stiffness (Figure 10). The static load of this trolley is 60 kN, the dynamic load is 20 kN and the maximum speed is 30 km/h. The trolley could not be used in the curves with radius lower than 1200 m or in switches. This trolley could be excited using different frequencies, but only one frequency for each run. Several tests with different combinations of excitation frequency and speed were carried out using this trolley in order to confirm repeatability of mesurements (Berggren, 2009; Wang et al., 2016).

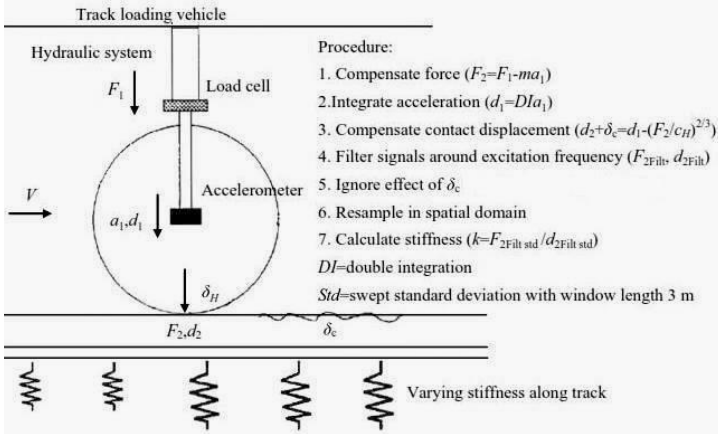

Figure 10. Principle of Banverket's trolley for continuous track stiffness measurement (Wang et al., 2016)

After development of the previously described trolley, Banverket and Royal Institute of Technology (KTH) in Sweden started the new research project. The aim of this project was improvement of the existing measurement technique through the development of the new vehicle named RSMV (Rolling Stiffness Measurement Vehicle). RSMV measures the quasi-static and dynamic vertical track stiffness, and determines the relation between track stiffness and degradation/maintenance of the track (Berggren, 2009). RSMV presents rebuilt two-axle freight wagon, supplied with the equipment for applying the load and conducting the measurements (Figure 11). The track is dynamically excited with two oscillating masses above one of the wheel axles (oscillating mass of 4,000 kg). The static axle load is 180 kN (or higher) and the maximum dynamic axle load amplitude is 60 kN. The RSMV could measure dynamic track stiffness at frequencies up to 50 Hz. It is possible to perform measurements at speed up to 50 km/h, as well as detailed tests at speed up to 10 km/h (INNOTRACK, 2006; Nielsen et al., 2013; Wang et al., 2016). The main advantage of using RSMV for investigation of ground-borne vibrations is its ability to detect resonance frequencies of track sections on soft soils (Nielsen et al., 2013).

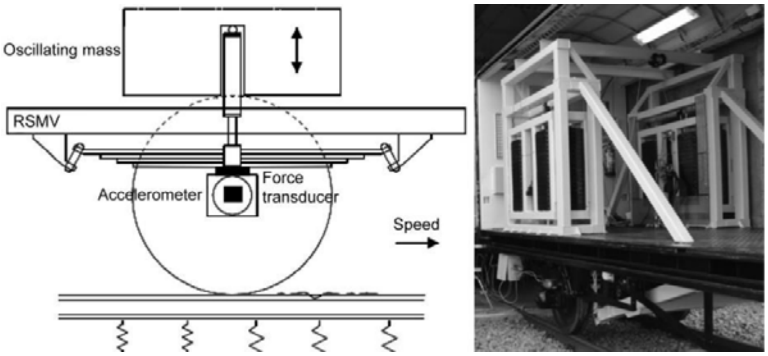

Figure 11. Measurement principle and equipment of RSMV (Wang et al., 2016)

Sponsored by the Innotrack project, the Centre d'Expérimentation et de Recherche and the Engineering Department of SNCF (French Railway Company), developed the Portancemetre vehicle with a vibrating wheelset for measurements of the dynamic track stiffness. This measurement vehicle consists of two parts, the measurement core system called demonstrator, and the technical carriage system (Figure 12, left). The static load of the Portancemetre may vary between 70 and 120 kN, and the maximum dynamic load amplitude may increase up to 70 kN. The Portancemetre can measure the stiffness by exciting the track with a frequency up to 35 Hz. The maximum measurement speed is about 15 km/h, due to the force–displacement hysteresis. The Portancemetre demonstrator is equipped by following sensors (Figure 12, right): unsprung mass accelerometer (vibrating wheelset), suspension mass accelerometer, phase sensor and incremental distance encoder (Hosseingholian et al., 2011; INNOTRACK, 2006; Wang et al., 2016).

Figure 12. Schematic view and on-site measurement with Portancemetre (left) and sensors on the Portancemetre demonstrator (right) (Hosseingholian et al., 2011)

Ensco and Volpe National Transportation System Center, sponsored by FRA (Federal Railroad Administration), carried out the research with the idea to mount accelerometers on two axles with different static load. The system is similar to TTCI and SBB. The measuring system is much simpler, and development of sensor technology would provide futher improvement in measurement accuracy (INNOTRACK, 2006).

The EVS method (EBER Vertical Stiffness) is based on two cases of track geometry measurements - the first case relates to the geometry irregularity of the unloaded track, and the second case relates to the track geometry due to the loaded axle. The aim of this method is to separate the unloaded track geometry and the loaded track geometry, in order to reduce the influence of track geometry irregularities on stiffness measurements. This method has been implemented on the Infranord vehicle IMV100, which has the ability to measure at speed up to 100 km/h. It was concluded that the method is suitable for detection of large variations in track stiffness due to the effect of hanging sleepers (Nielsen et al., 2013).

4. CONCLUSION

Maintenance of railway lines is mainly based on the application of inspection methods for the superstructure, while the condition of the substructure is often unknown and only limited to visual inspection. The poor track foundation (including the substructure) could lead to a decrease of track geometry quality, and further to the increased dynamic load of the whole track structure and faster track geometry degradation, as well as deterioration of other components of the track structure (Hosseingholian et al., 2011; INNOTRACK, 2006; Puzavac et al., 2012).

The track stiffness measurement is significant for the design of new railway lines, upgrading of existing railway lines for higher axle load and speed, as well as for railway maintenance works. Results of stiffness measurements could be used as the indicator of track geometry deterioration, hanging sleepers, as well as for evaluation of transition zones (INNOTRACK, 2006; Lazarević et al., 2016; Nielsen et al., 2013).

The paper describes the existing standstill and continuous methods for track stiffness measurements. The methods for standstill track stiffness measurements are: time consuming, generally applicable for shorter track sections, and requiring track closure or longer stop of traffic for conducting measurements. In addition, they could not provide the information related to the stiffness variation along the railway line. Due to the neccessity to conduct measurements on the level of railway network, different methods and vehicles for continuous stiffness measurements were developed in order to realise optimal track maintenance. However, a few Infrastructure Managers have the ability to provide vehicles for the continuous track stiffness measurement, primarily due to their price (INNOTRACK, 2006).

The information about the track stiffness depends to a large extent on the analysis of the measured data. Up to now, there are no quantitative research on the relation between track stiffness and applied load, running speed, and the exciting frequency, which is the main reason for inadequate analysis of continuous track stiffness data (Wang et al., 2016).

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5. REFERENCES

Berggren, E. (2009). Railway track stiffness: dynamic measurements and evaluation for efficient maintenance (Doctoral dissertation, KTH).

Greisen, C. J. (2010). Measurement, simulation, and analysis of the mechanical response of railroad track (Doctoral dissertation, University of Nebraska at Lincoln).

Hosseingholian, M., Froumentin, M., & Lavacher, D. (2009). Continuous method to measure track stiffness a new tool for inspection of rail infrastructure. *World Applied Sciences Journal, 6*(5), 579-589.

Hosseingholian, M., Froumentin, M., & Robinet, A. (2011, May 22-26). Dynamic track modulus from measurement of track acceleration by portancemetre. In 9th world congress on railway research.

INNOTRACK. Methods of track stiffness measurements. Report D2.1.11, 2006.

Kouroussis, G., Caucheteur, C., Kinet, D., Alexandrou, G., Verlinden, O., & Moeyaert, V. (2015). Review of trackside monitoring solutions: from strain gages to optical fibre sensors. *Sensors, 15*(8), 20115-20139.

Lazarević, L., Vučković, D., & Popović, Z. (2016). Assessment of sleeper support conditions using micro-tremor analysis. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 230*(8), 1828-1841.

Molatefi, H., & Mozafari, H. (2013). Analysis of new method for vertical load measurement in the barycenter of the rail web by using FEM. *Measurement, 46*(8), 2313-2323.

Nielsen, J., Berggren, E., Lölgen, T., Müller, R., Stallaert, B., & Pesqueux, L. (2013). Overview of methods for measurement of track irregularities important for ground-borne vibration. *Railway Induced Vibration Abatement Solutions (RIVAS)*.

Popović, Z., & Radović, V. (2013). Analysis of cracking on running surface of rails. *Građevinar, 65*(03.), 251-259.

Popović, Z., Lazarević, L., Brajović, L., & Vilotijević, M. (2015). The Importance of Rail Inspections in the Urban Area-Aspect of Head Checking Rail Defects. *Procedia Engineering, 117*, 596-608.

Puzavac, L., Popović, Z., & Lazarević, L. (2012). Influence of track stiffness on track behaviour under vertical load. *PROMET-Traffic&Transportation, 24*(5), 405-412.

Wang, P., Wang, L., Chen, R., Xu, J., Xu, J., & Gao, M. (2016). Overview and outlook on railway track stiffness measurement. *Journal of Modern Transportation, 24*(2), 89-102.

http://bsh-muc.com/ , 28.06.2017.

http://www.drgw.net/trips/report.php?tr=TTCI.3, 28.06.2017.

http://www.macben.be/s9-draagkracht/?lang=en, 28.06.2017.

https://www.slideshare.net/RailwaysandHarbours/rail-deflection, 28.06.2017.