Broj rada: 8(2010)3,179, 117-122

FLAT WHEEL DETECTION AS A PART OF WAYSIDE TRAIN MONITORING SYSTEMS

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Flat spots and other imperfections in wheel roundness stress the railway superstructure and can cause expensive damages. Moreover, in critical situations, where several disadvantageous conditions of railway vehicles and/or infrastructure arise at the same time, flat spots may result in heavy accidents. Thus the early recognition of flat spots is an important task. In the past sensor systems have been developed, which use different algorithms to estimate size and shape of the flat spots as well as they use different types of specification. But most of them seem not be suitable to evaluate the consequences caused by the flat spots' impacts. Thus, the authors of this article suggest usage of an effect-equivalent flat spot for all imperfections of wheel geometry.

Key words: wheel, imperfections, detection

INTRODUCTION

Flat spot is a term for a plane area on the running surface of a railway vehicle's wheel. In general, this defective area arises, if a wagon moves with locked wheels due to heavy braking or brakes being stuck. Wheel and rail are made of steel with comparable rigidity. Thus, friction between them leads to an abrasion of material. Because of the movement of the train, abrasion on the rail is spatially expanded and therefore very small. However, the wheel slides along the rail, the same spot touching it all along and friction causes removal of a segment ("flat spot"). Sometimes abraded material is reattached to the wheel at one end of the spot. Such a convexity on the running surface of a wheel is called rewelding.

Besides flat spots and reweldings there are other irregularities of the running surface of a wheel. Ovality and out-of-roundness are small imperfections in the circularity. If the shape of a wheel comprises several flat spots and equals a polygon, this condition is called polygonisation. Furthermore, small waves all around the running surface are named ripples.

Consequences of wheel imperfections

Neglecting vehicle body movements and other changes of the wheel load, an ideal circular shaped wheel will induce a vertically constant force on the rail over the whole rotation. Due to mentioned faulty running surfaces additional forces act on the rail during the wheel rotation, causing total forces on the rail with minima and maxima. Especially the latter ones stress the rail, the bearings and other parts of the bogie. The total amount of stress and thus the risk of dangerous situations due to mechanical damage depends on many different parameters:

- dimension and shape of the surface fault
- wheel rotation speed, respectively wheel diameter and vehicle speed
- wheel load
- mass of wheel and wheel set
- type and properties of vehicle suspension
- etc.

Heavy impacts of an unround wheel can cause micro cracks in the wheel surface and further ablation of the material. The resulting magnification of the induced stress may cause heavy damage of the wheel and possibly entails a derailment. The impacts can also damage components of the axle bearings, which could lead to massive overheating. The last consequence of such a hot box is breaking away the axle stub and subsequently a derailment.

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On the infrastructure side low ambient temperatures decrease the elasticity of the rail. Under such harsh conditions, heavy impacts result in dissociation of pieces or rail cracks.

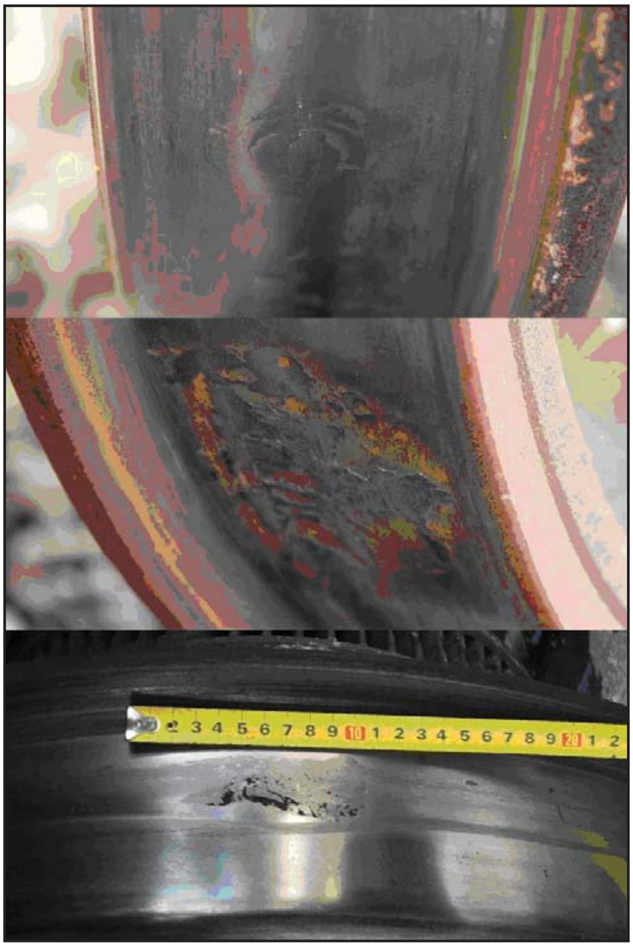

Fig.1. Examples of flat spots

Limiting values

For preventing dangerous situations or accidents, there are limiting values for the maximum length of flat spots for railway operation defined by the UIC (International Union of Railways) [3]. These values depend on the maximum speed of the vehicle and the wheel diameter (Table 1).

Table 1. Maximum length of a flat spot

Wheel Diameter (mm)	maximum length of flat spot (mm)		
	vmax ≤ 160 km/h	vmax ≤ 200 km/h	vmax > 200 km/h
330 - 630	≤ 30	not allowed	
630 - 1000	≤ 60	≤ 30	not defined

Alteration of wheel irregularities

Even if ovalities of wheels are within these limits, they induce variations in the vertical force, especially at high speeds. This in turn amplifies wear of the running surface and the ovalites mostly will enlarge [8]. Thus, the characteristics of such out-of-roundness are not static, but rather alter over time.

Flat spot characteristics behave similar. The shape will change because of wheel wear. If a vehicle is equipped with wheel brakes the mentioned alteration will happen faster, because such brakes abrade on the running surface during brake activity. Wear effects that the edges of flat spots become smoother and flat spot forms will deviate from the original segment of a circle. Also the edges of polygonised wheels will not always be shaped very exactly.

MEASUREMENT SYSTEMS

Defective wheels have to be identified fast to keep the risk of accidents or damages to the superstructure at a minimum. In the past train inspection was done by station inspectors. Nowadays, due to economic reasons railway operators use more and more technical solutions [1], which substitute the human supervision [4].

Accoustic Detection

Devices for acoustic detection of flat spots use an electro-acoustic transducer located on the track to pick up vibrations generated by the train. Such devices provide a spectrum of electrical signals corresponding to the vibrations. The sound of a passing train is recorded and the part caused by a flat spot is distinguished by the frequencies. This measurement principle is influenced by surrounding noise and therefore not suitable for an application in railway operation.

Detection based on Wheel Flange Position

The measurement site consists of four parts: A parallelogram mechanism, a displacement transducer, a data collecting and processing system and a computer and communication system. When a train passes the measurement site the flange top of the wheel will press down the long beam in the parallelogram mechanism. Any vertical movements will be detected by the non-contact displacement transducer which faces to the long beam. In practical application the signals are quite different from ideal ones because of various manufacturing and assembling errors.

Detection with Electrical Continuity

This method for detection of flat spots is based upon the changes in voltage resulting from a break in an established circuit caused by a flat spot. To detect flat spots also on a wheel with conductive material, a current circuit is used. The voltage source may be a DC source of an AC source and having one terminal connected to the first rail and another terminal connected to the second one. A break in the current circuit as a result of a flat spot can be detected by sensing the voltage over a portion of the impedance or by inductively sensing the current in the current circuit.

Optical Detection

Detectors will identify flat spots passing at any speed by measuring the greater distance between the wheel flange rim and the central portion of the flat sector on any railcar wheel having a significant flat portion on its tread. Whenever a flat spot passes the detector with its flat sector arriving at the supporting rail, the lowered rim flange reduces the amount of light radiation detected by one or more photocells, producing a signal to record data of identifying wheel, vehicle and train for future interception and wheel replacement.

Detection with Piezoeletric Elements

Such devices consist of two treadles to detect the wheel passage and two wheel flat detectors mounted in a cross layout. This geometry allows an optimal detection of flat spots presented in a diametrically opposite position. The treadles should be absolutely insensitive to rail vibrations and electromagnetic interference. The detectors are made of a special clamp with a leaf spring that pre-loads a small aluminum block on which a short length of piezoelectric element is mounted.

Detection by Dynamic Force Measurement

Most of these detection systems measure the peak force and relate it to the wheel load and other acquired measurands to evaluate the exact flat spot dimension or recognize other irregularities in the wheel geometry. An example of such a sensor system is shown in Fig. 2: strain gauges applied to the rail detect the bending of the rail, which depends on the exerted vertical force.

Fig.2. Dynamic scale and flat spot detection of Austrian Federal Railways (Infrastruktur Betrieb AG)

Detection by Measurement of Acceleration

Acceleration sensors mounted on the rail are also able to measure flat spots by their impact. The vibration of the rail or of the sleepers is used as an indicator and is directly related to the speed of the passing train. Therefore the accuracy is lower at higher speeds. At low speed the impact of a flat spot can be also lower due to missing energy.

Detection with Laser-based Technology

The laser-based system measures the forces generated by the passing trains due to a deflection of the laser beam. The system identifies and quantifies the size of flat spots. The receiver element consists of a charged coupled array device. As distortion is caused in the rail by loading forces, the laser and receiver are displaced relative to each other, and the beam sweeps across the charged coupled array device producing the output signal.

Summary of all measurement systems

The quality of the calculated results is difficult to verify as the report from SBB on their measurement site in Osogna has clearly shown [5]. Even for test trains, the correct length or depth of a flat spot is difficult to determine (mostly the flat spot's borders are blurred, as in Fig. 1 depicted). The calculation algorithms – used by the manufacturers - are often very complex and closed. Therefore an infrastructure manager as a potential operator has no knowledge of the quality of the flat spot evaluation.

ALTERNATIVE DESCRIPTION

Basic idea

For the infrastructure manager as well as for the service manager, the increased material stress should be avoided to prevent the material from damage. Thereby, the detailed knowledge of the shaping is useless. Primarily the created material stress is of importance.

On the other hand and as mentioned above, the limiting values of the UIC (Table 1) refer to the length of a flat spot. This is more or less reasonable in consideration of verifying a flat spot when the vehicle does not move (e.g. in a service center). But this threshold definition neglects various characteristics of flat spots, reweldings and other defects in wheel roundness. For instance, a flat spot without rewelding may cause much lower impacts than a flat spot of the same length including an additional rewelding. Thus the length-based evaluation does not perfectly meet the requirements for saving superstructure damages and preventing accident-prone situations.

From this point of view, the essential criterion of flat spots or other imperfections of the wheel roundness is the peak of the force on the rail generated. Thus, the actual type of failure is irrelevant. But solely characterising the irregularities based on the acting peak forces is not significant enough. For example, if the vehicle velocity changes, peak forces of the same flat spot will widely vary, too. So to ensure a complete characterisation of the surface failures it is necessary to specify peak values and further basic criterions at the same time. This description is cumbersomely and difficult to interpret.

To be in accordance with the limiting values of UIC, a transformation of force peaks to lengths of an idealized effect-equivalent flat spot is advantageous. The conversion has to be simple and comprehensible. Changeable parameters have to be taken into account in order to get statically valid flat spot lengths. Furthermore, the calculation algorithm has to be applicable for all types of vehicles. Due to this, simplifying assumptions have to be made for transformation. This procedure seems to have negative effects on the accuracy of the results. But in the end the effect-equivalent length is just virtual and only used to estimate the dimension of the failure.

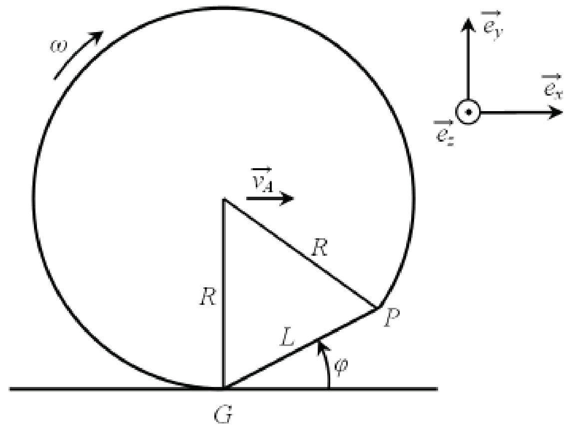

Fig.3. Geometry of a railway vehicle wheel with an idealized flat spot

Mathematical derivation

Consider a railway vehicle wheel of radius R with an idealized flat spot of length L at an instant of time at which the impact effect of the flat spot on the rail sets off (Fig. 3). Since at this instant of time point G of the rotating wheel is in contact with the rail, point G is the instantaneous center of rotation of the wheel, and the velocity of point P can be calculated using the basic formula for the velocity field of a rigid body [6].

$$\vec{v}_P = L\omega\left(\sin(\varphi)\,\vec{e}_x - \cos(\varphi)\,\vec{e}_y\right) \qquad (1)$$

where ω is the angular velocity of the wheel and φ is the angle between the flat spot and the rail (Fig. 3) and ex i ey unit vectors of cylindrical coordinates. Note that ω = vA/R, where vA is the speed of the railway vehicle.

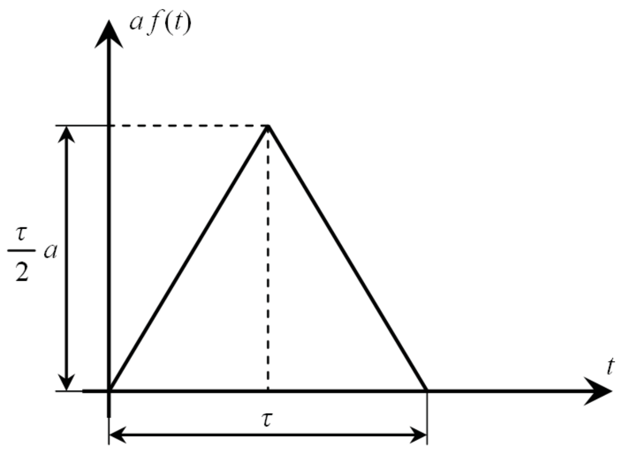

Fig.4. Transient loading of the rail

The impact of the flat spot on the rail is a process of momentum exchange between the wheel and the rail within a short time of contact τ which is inversely proportional to vA. Thus τ = k/vA, where k is a constant of physical dimension of length. With respect to the impacted structure (the rail), the loading in such a process acts with high intensity during this short period of time (τ). It is thus assumed that the time function f (t) of the loading at any point of contact has a triangular shape (Fig. 4), and the normal stress in the rail σ is then given by

$$\sigma = -a\, f(t)\,\delta(x)\,\delta(z) \tag{2}$$

where the constant a specifies the intensity of the loading, and δ(x) and δ(z) are the Dirac delta functions . Since the physical dimension of a is force per time, the physical dimension of the area of the triangle shown in Fig. 4 is force times time which is the physical dimension of the momentum. The area of this triangle can be interpreted as the amount of momentum communicated to the rail so

$$m\left|v_{Py}\right| = \frac{1}{4}\tau^2 a \tag{3}$$

where m is the railway vehicle mass per wheel, and vPy is the y-component of vP given by equation (1), that is, vPy = –Lω cos(φ). Since L is small compared with R,

φ << 1 and the expression for |vPy| takes the form of

$$\left|v_{Py}\right| = \frac{v_A}{R} L \tag{4}$$

where the relation ω = vA/R has been used. In view of this result (4), from equation (3) follows

$$a = 4\,\frac{m\,L\,v_A}{\tau^2 R} \tag{5}$$

Substituting equation (5) into equation (2), noting that the peak value of f (t) is τ/2 (Fig. 4) and recalling that τ = k/vA, the peak value of the normal stress is

$$\sigma = -2\,\frac{m\,L\,v_A^2}{k\,R}\,\delta(x)\,\delta(z) \tag{6}$$

and the peak value of the vertical loading of the rail is

(*Dirac delta functions are generalized functions representing an infinitely sharp peaks bounding unit areas: ‘functions’ δ(x) and δ(z) that have the value zero everywhere except at x = 0 and z = 0 where values are infinitely large in such ways that total integral is 1. In the context of signal processing often are referred as the unit impulse functions.)*

$$F_{max} = \sigma_{max}\; L\, b \tag{7}$$

where b denotes the width of the flat spot.

Result

The combination of equation (6) and (7) shows the desired relations between force peaks Fmax, effect-equivalent flat spot length L, vehicle velocity V_A and wheel load m

$$F_{max} = f_1\left(\frac{m\,L^2\,v_A^2}{R}\right), \quad L = f_2\left(\sqrt{\frac{F_{max}\,R}{m\,v_A^2}}\right) \tag{8}$$

f1 and f2 symbolize a linear relationship, which can be quantified from (6) and (7).

OUTLOOK

With the help of the derived theoretical relation between the measurable stress on the rail and the effect-equivalent flat spot length wheel failures on the running surface can easily be assessed and compared. For achieving high acceptance of the discussed evaluation approach for wheel failures, a corresponding adoption of [3] would be desirable.

The next step is a practical verification of this approach. Since 2003 an overall system for train inspection is installed on one of the main lines of Austrian Federal Railways [4], which is called “Checkpoint”. It comprises several sensor systems. Among others there are dynamic scales installed, which are able to detect the wheel load, as well as the peak force over the whole circumference. One Checkpoint of Austrian Federal Railways is going to be installed this year on Corridor X between stations Batajnica and Nova Pazova [7, 2, 9]. Test runs helped to evaluate the abilities and reliabilities of the whole systems. Thereby vehicles prepared to represent certain failures (flat spots, rearranged cargo, etc.) were used. The stored data of the test runs and future data of daily traffic will be the base for the comprehensive examination of the approach presented.

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OTKRIVANJE RAVNIH MESTA NA TOČKOVIMA KAO DEO SISTEMA ZA PRAĆENJE STANJA ŽELEZNIČKIH VOZILA U SAOBRAĆAJU

Ravna mesta i druge nepravilnosti na površini kotrljanja točka opterećuju gornji stroj pruge i mogu da dovedu do skupih oštećenja. Dalje, u kritičnim situacijama kada dođe do istovremenog narastanja negativnih stanja železničkih vozila i/ili infrastrukture, ravna mesta mogu dovesti do teških nezgoda. Zato je rano otkrivanje ravnih mesta važan zadatak. U prošlosti su razvijeni sistemi davača koji koriste različite algoritme za procenu veličine i oblika ravnih mesta, a takođe imaju i različite karakteristike. Ali, čini se da većina od njih nije pogodna za procenu posledica koje izazivaju udari ravnih mesta. Stoga, autori ovog rada preporučuju korišćenje ekvivalenta uticaja ravnog mesta za sve nepravilnosti geometrije točka.

Ključne reči: točak, nepravilnosti, otkrivanje

Rad poslat na recenziju: 01.06.2010.
Rad spreman za objavu: 03.08.2010.