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OUT-OF-ROUND TRAM WHEELS – CURRENT STATE AND MEASUREMENTS

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Abstract:

Railway or tram wheel is never perfectly round and its surface is not ideally smooth, even at the very moment after manufacturing. This induces dynamic interaction between wheel and rail while rolling, which may result in accelerated wear, fatigue cracking, corrugation formation (both on wheels and rails) and intensified vibroacoustic emission. This paper is an attempt of summarising the current scientific achievements concerning out-of-round (OOR) tram wheels. The gathered research may provide an introduction to the broader analysis of this issue in tram technology. However there is still very little scientific works dedicated directly to light rail vehicles such as trams. The measuring methodology of out-of-round tram wheels is also described in this article. Appropriate measurements were made on the wheels of selected vehicles operated by municipal tram company in Poznań. The obtained results allowed to learn the characteristic forms of out-of-round tram wheels, among which, several forms of polygonization (ovalization, triangularization, etc.) were observed. Therefore we confirmed the thesis, that the method of fixing tram wheel rims in the lathe has a significant effect on formation of the unevenness of its rolling surface, both when new (just after turning) and, after some mileage of use, when even small irregularities become amplified. We observed also that the amplitude values from 5th up to 10th harmonic orders were increased during the operation. The initial out-of-round shape of the wheel should be likely present on the worn wheel, but with increased amplitudes of irregularities. Wheel out-of-roundness should be identified and removed at the soonest possible state to prevent its development and generating issues in the future operation, that are for example: rolling stock and infrastructure damage, impaired comfort of passengers and city inhabitants. It makes out-of-round wheels a serious problem to cope with for the vehicle operators, which can lead even to a catastrophe.

Key words:
tram wheel, out-of-roundness, untrueness, polygonization

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1. Introduction

In times of increased demand for the efficient transportation of people, public transport provides a very attractive solution to the problem of crowded cities. The most efficient type of urban transport is rail transport. In Poland, the most popular choice in this category is the tram. However, despite the unquestionable benefits cities derive from having this type of public transport, disadvantages also exist, one of which being the emission of vibroacoustic phenomena. Complaints from people living in areas adjacent to tram lines stem from excessive vibrations and noise, and can sometimes damage nearby buildings. Most of these effects originate from the contact of the wheel with the rail, or they are transferred through the track to the environment. The aforementioned effects are caused by discontinuities or irregularities of the rails (e.g. corrugation), missing or deficient characteristics of vibration damping elements between the track and the environment, and out-of-round tram wheels (Chudzikiewicz, Sowiński and Szulczyk, 2009; Thompson, 2009). Vibration and noise emission to the environment is significantly intensified by the roughness of the rolling surface (wheel-rail) (Thron and Hecht, 2010). Large cities have dense population, hence the additional noise emissions of polygonized tram wheels will be a much greater nuisance than those produced by trains.

In the rest of this paper, the current state of scientific knowledge is presented, which may pave the way for future considerations on the subject of trams.

2. Related research about wheel out-of-roundness phenomenon

Deformities in the shape of the rolling surface of wheels can come in many different forms, and are influenced by the process of their formation. Rail vehicle wheels often experience a type of fatigue wear called RCF (rolling contact fatigue) by the rail industry, which is a result of cyclical material stress, rapid temperature changes, or manufacturing defects. The result of this phenomenon is spalling, shelling of the material, and even rupture of the rim through the propagation of surface cracks in the material (Johansson, 2006; Nielsen, 2011). The deviation of the shape of the wheel from a perfect circle can take the forms presented in Figure 1. Due to the induced vibrations and dynamic stress, they are a serious threat to the elements of the track and the vehicle, and may cause structural fracture and rolling contact fatigue to the wheels, axles, and bearings (Nielsen, 2011). OOR wheels cause vibrations with one or more component frequencies in the vehicle-track system (Iwnicki, 2006).

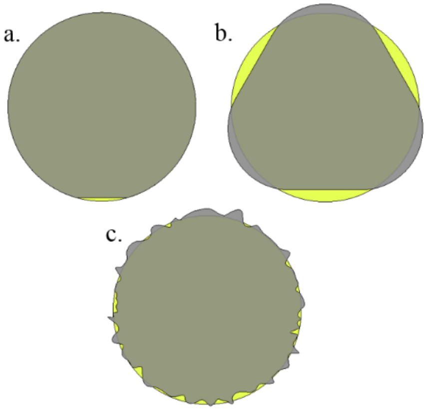

Fig. 1. Forms of OOR wheels (exaggerated for exemplary purposes), description in text

Due to the frequent, intensive braking in urban traffic, tram wheels present tendency to develop flat areas (Figure 1a). They are formed on the wheel rolling surface when the vehicle is moving with blocked rotational movement of wheels, so the material is abraded in one spot on the rolling surface. At this point, the flat surface is already present on the rolling surface of the wheel. Furthermore, after regaining adhesion, the hot part of the wheel is rapidly cooled in contact with the cold rail, which could potentially cause the structure of the metal material to change. Small areas of martensite can form, in which high compressive stresses (inside martensite area) and tensile stresses (around martensite area) are generated. This causes the material of the wheel to crumble and may lead to further cracking (Lewis et al., 2010). On the other hand, the residual, softer material of the wheel rim will wear (due to friction) faster than the thermally hardened one (martensite areas) (Chudzikiewicz, Sowiński and Szulczyk, 2009). Wheel flats have an adverse impact at the wheel-rail interface in the form of regular, pulse impacts, with a frequency proportional to the wheel rotational speed. This can lead to cracking of the wheel and rail surfaces, as well as cracking deep into the material and critical failures in the future (Iwnicki, 2006). Flat areas may also appear due to the non-uniform structure of the wheel rim material (Nielsen and Johansson, 2000; Vakulenko et al., 2016).

OOR wheels can also take the form of regular, rounded polygons (Figure 1b). This is called the polygonization of wheels and generates higher frequency wheel vibrations than wheels with single flat spots (Chudzikiewicz, Sowiński and Szulczyk, 2009; Nielsen, 2011). In the case of railways, these irregularities usually come in 1-5 different wavelengths around the circumference of the rim, with amplitudes in the order of 1 mm (Nielsen, 2011). Related research papers describe the specific harmonic components of the OOR irregularities, whose wavelengths are determined by:

$$\lambda = \frac{2\pi R}{\Theta} \tag{1}$$

where: $\Theta = 1, 2, 3, \ldots$ – harmonic components, R – wheel radius.

Figure 2 shows examples of harmonic components of wheel shape irregularities. The example in Figure 2a shows the eccentricity of the wheel caused by manufacturing inaccuracies during the rolling of the wheel (the axis of the wheel during the rolling process does not correspond to the rotational axis of the wheel during use). Every rolled wheel possesses this type of irregularity to a certain extent. According to (Nielsen and Johansson, 2000) the other two forms of periodic irregularities of higher orders are found in the railway mostly on wheel sets that are fitted with disc brakes, but also due to errors in rolling wheel profiles. These errors can be amplified during operation, resulting in an increasing dynamic impact on the vehicle-track system. The wavelengths of such inequalities (several may occur) reach a length of range from several centimeters to a dimension close to the circumference of the rolling surface (Nielsen and Johansson, 2000).

Ovalized wheel of harmonic component 2 is presented in Figure 3. The dominating harmonic components are 1 and 2

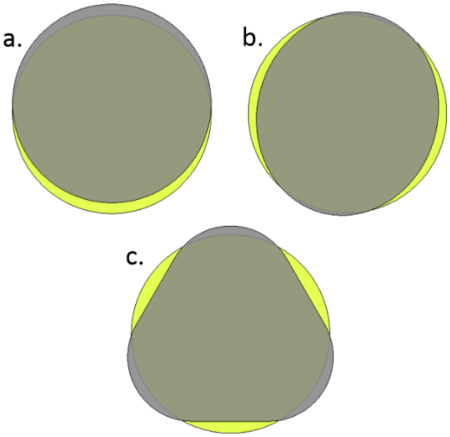

Fig. 2. Examples of harmonic components of wheel irregularities (exaggerated for exemplary purposes), description in text

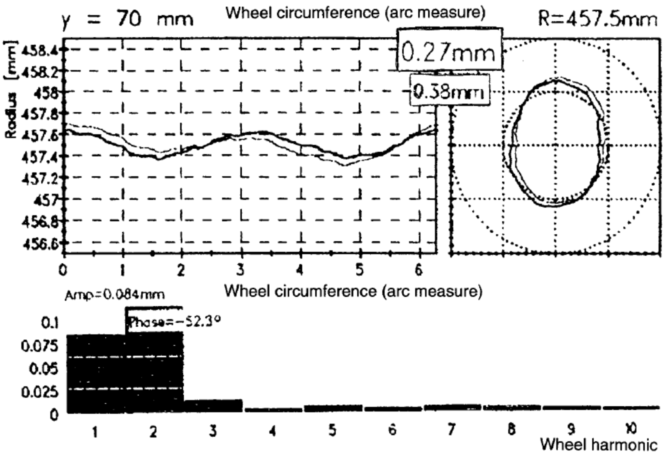

Fig. 3. Results of the measurement of the ovalized wheel (Pallgen, 1998)

There are also cases of wheel irregularities lacking periodic character (Figure 1c). Such cases are observed only on wheels fitted with disc brakes (Nielsen and Johansson, 2000; Iwnicki, 2006). The distribution of harmonic components with this irregularity is characteristic and spread out wide, over many orders (Figure 4) (Nielsen and Johansson, 2000).

It should be mentioned that any unevenness of the rolling surface, or deviation in the rolling radius will most likely cause an intensification of vibroacoustic effects, including of course noise. Due to the above, as well as risking damage to infrastructure and rolling stock, wheels with OOR of the rolling surface should be immediately withdrawn from operation and reprofiled. It is clear, therefore, that there is a need for an effective, systematic method for the identification of defective wheels with a separate device located, for example, on the depot track. This way, all operational trams will have their wheels checked every day (Czechyra, Firlik and Nowakowski, 2015).

Even after a short period of operation, slight OOR in the rolling surface of the wheel can become noticeable. These irregularities increase very quickly during further operation. Wheels with irregularities of the harmonic components of the third or fourth order on a rigid track may have a tendency to bounce, so the wheel and rail may be temporarily without contact. In addition, OOR wheels result in significant variations in normal forces during operation which affect the wheel axle or portal axis causing bending. This in turn, causes the wheel to slide on the rail in the lateral direction when there is enough rigidity in the wheel-axis connection as well as in the wheel itself. This phenomenon may be responsible for accelerating the wear of the wheels and rails, and is the main cause in increasing the existing wheel irregularities, intensifying the negative impact. It follows from the above that the irregularities of the radius of the wheel should be monitored and, if necessary, corrected in turning process.

In years 2006-2008 a research project was carried out on the simulation of running wheels with irregular radii named "SIMOOR - Simulation of Out-Of-Roundness of Railway Wheels" (Bureau of Applied Mechanics and Mathematics, no date). In this work, a simulation tool for modelling the movement of wheels with irregular rolling radii was developed to understand better the phenomena occurring at the rail-wheel contact point. It allowed for the prediction of operation of the wheel concerning its evolving shape of the entire rolling surface, not just its profile (cross section). The authors of the project found that the wheel OOR is responsible for reduced comfort and safety, destructive effects on rolling stock and infrastructure, and increased emissions of vibrations and noise to the environment. Therefore, it was emphasized that frequent and thorough inspections of the wheel radius of rail vehicles are necessary to detect the problem at an early stage resulting in reduced maintenance costs. Due to the fact that the wheels of smaller diameters need to make more rotations to travel the same distance as larger wheels, this can be especially significant in the case of trams, whose wheels are much smaller than train wheels (Barkow and Mittermayr, 2008).

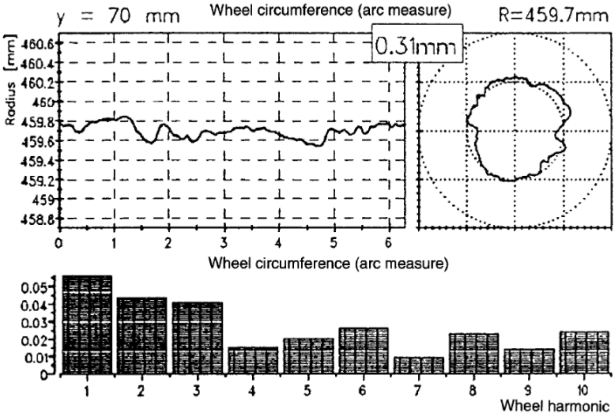

Fig. 4. Results of a wheel measurement with irregular rolling radii (Pallgen, 1998)

As described in paper (Han, Jing and Liu, 2017) dynamic loads increase as the flat area increases. In addition, in most cases, the dynamic loads are also proportional to the speed of travel. Opposite results in this aspect were obtained by Martínez-Casas et al. (Martinez-Casas et al., 2015), during simulation of ride on a flexible track with flexible wheelsets. It followed that as the speed increased, the peak load between the wheel and the rail decreased. It was found that OOR magnitude generally decreases in correlation with higher harmonic order, as shown in (Johansson and Andersson, 2005). Furthermore, the wheel polygonization of harmonic component of the third or fourth order may be down to the method of fixing the wheel in the lathe. Results for the influence of the wheel fixing method on the OOR are presented further on in this paper. As noted before, even small irregularities in the wheel rolling radius can in the short term become a rather serious problem, increasing significantly and adversely affecting rolling stock and infrastructure.

The paper by Martinez-Casas et al. shows part of the results of vehicle-track interaction studies, carried out using a mathematical model (Martinez-Casas et al., 2014). The authors analysed, among other examples, the performance of a wheelset with 50 mm long flat spot on the rolling surface with the same rotational position for both wheels. Dynamic loads when travelling in curves in these conditions exceeded 330% of the static load value. Riding in a tangent track gave significantly lower dynamic load values. It follows that flat spots can be more problematic when riding through curves due to faster degradation of the track and vehicle components and intensification of vibroacoustic emissions to the environment. It was also noted that the outer wheel experienced higher lateral loads than the inner wheel. The reason for this is the displacement of the wheelset towards the outside of the track, which generates a greater angle for the inside wheel at the point of contact with the rail. The difference in results for the rigid and flexible wheel model was small in relation to the duration of contact loss, and the maximum load in the lateral direction (however, differences in impulse damping functions were observed). In the case of maximum forces in the longitudinal and vertical directions, the rigid model obtained results overestimated by about 20%. However the application of flexible models and driving in curves to analyze the dynamic impact of flat areas is still relatively rare. This work clearly demonstrated that it is necessary to use these models for analysing the differences in results in relation to utilizing straight track, rigid track, and rigid wheelset.

The European standard EN 15313 defines the non-mandatory limits for the amplitude of OOR railway wheels (Table 1).

Table 1. Allowed values for the amplitude of OOR railway wheels, adapted from (EN 15313)

Wheel diameter - dependent speed	Permitted OOR (Δr)
$D > 840$ mm	
• $v_{max} \leq 60$ km/h	1,5
• 60 km/h $< v_{max} \leq 160$ km/h	1,0
• 160 km/h $< v_{max} \leq 200$ km/h	0,7
• $v_{max} > 200$ km/h	0,5
340 mm $< D \leq 840$ mm	
• $v_{max} \leq 200$ km/h	0,7
• $v_{max} > 200$ km/h	0,5
$D \leq 340$ mm	0,3

The maximum tram operation speed in Poland is 70 km/h and the diameter of the wheel is between 500-700 mm, hence the permitted OOR limit is 0.7 mm. However, it is worth noting that this pertains to the railway industry. Tram regulations currently used in Poland define ovalization limit value of the machined wheel rim as 0.5 mm (PN-K-92012) and the radial runout of the rolling surface is 0.2 mm (PN-K-92016).

3. Measurement methodology

New and used tram wheel rims were acquired from municipal tram operator in Poznan for investigation. Measurements of the rolling radii were carried out (57.5 mm from the wheel gauge face) along the entire circumference of the rim. The measurement plane is shown in Fig. 5. Measurement plane for the rim radius. All rims had to be removed from their wheels and cleaned before the measurements could take place.

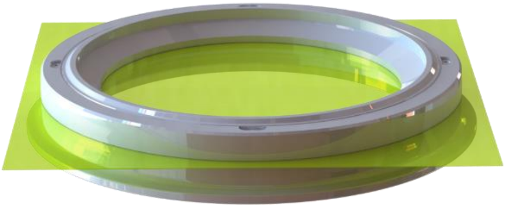

Fig. 5. Measurement plane for the rim radius

Two sets of wheels (one worn and one new) from three vehicles were measured: Solaris Tramino S105p, Düwag GT8, Konstal 105Na. Altogether, six wheels were measured. Tram wheel rim measurements were made using the WENZEL coordinate measuring machine, using the contact method. The sensitivity of the measuring instrument was 1.6 µm. The measurement consisted of tracking the outline of the wheel rim curvature with a ruby sphere mounted on the slider of the measuring machine. For various reasons, some wheels did not rest parallel to the surface of the table, which was adjusted for by the coordinate measuring machine through assuming an appropriate reference system.

4. Measurement results

Based on the mean values of the test results, the diameters of the measured wheels (rounded to 1 mm) were examined and presented in Table 2.

Table 2. Diameters of measured wheels [mm]

	Tramino S105p	Düewag GT8	Konstal 105Na
New	620	670	654
Worn	551	667	604

Figure 6 shows a graphical representation of the measurement results of the new Tramino S105p wheel. The polar graph shows the correlation between the value of the deviation and the angular coordinate. The red circle is the mean value of the deviation, i.e. it shows the position of the individual deviations relative to the diameter of the wheel being measured.

It follows that the new rim of the Tramino S105p vehicle carries traces of the machining process used during manufacturing. It can be assumed that the rim was fixed at three points in the lathe – the third harmonic component reached relative high value. The magnitude of the second harmonic component was even higher, which shows in the ovalization of the rim. In addition, there are numerous local increases in the radius of the order of hundredths of a millimetre, perhaps the traces of turning technology. The spread of values was about 0.06 mm.

Figure 7 shows a graphical representation of the measurement results of the worn Tramino S105p wheel. The polar graph shows the correlation between the value of the deviation and the angular coordinate. The red circle is the mean value of the deviation, i.e. it shows the position of the individual deviations relative to the diameter of the wheel being measured.

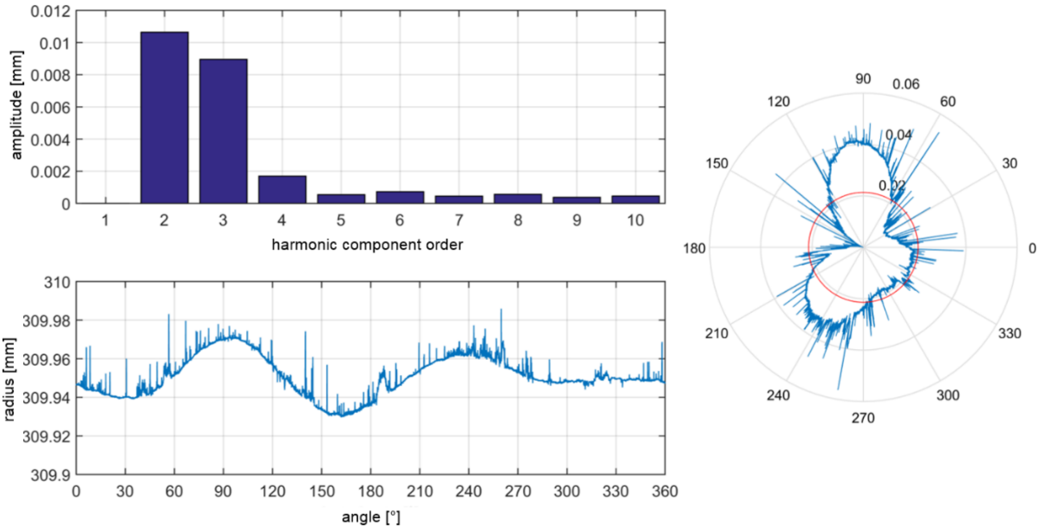

Fig. 6. Graphical representation of the measurement results of the new Tramino S105p wheel

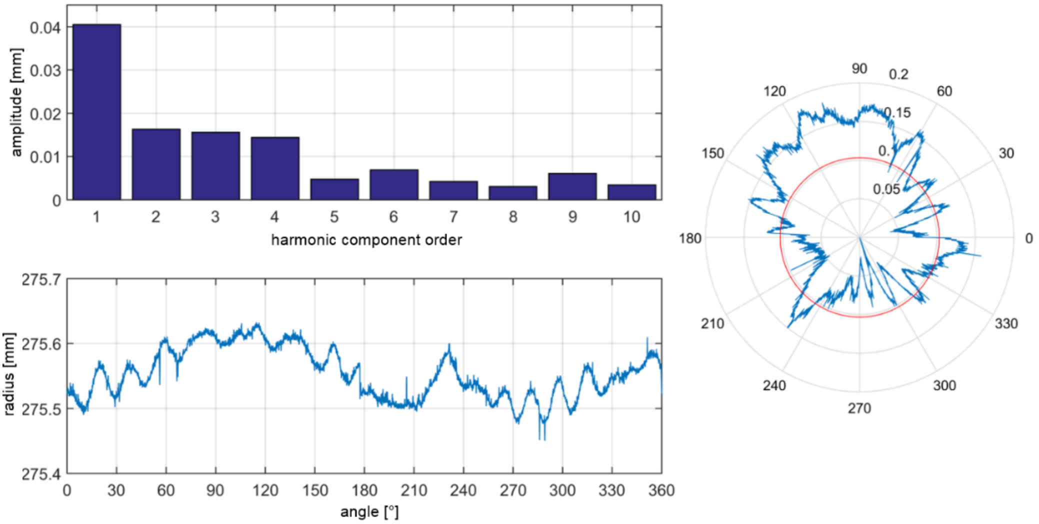

Fig.7. Graphical representation of the measurement results of the used Tramino S105p wheel

After analysing the graphs above, it can be seen that as the wheel becomes more worn, OOR amplitudes radius of the wheel increase in value, while also increasing their intensity for the harmonic components of higher orders. The dominant component for this wheel was the first harmonic component. A polar graph fragment between 70 and 150° differs from the rest of the wheel, with higher values of the radius of just over 0.05 mm. The graph also shows that the spread of values was approximately 0.18 mm. The traces of the turning technology seen in the measurements of the new wheel are not visible on the worn wheel, but some local deviations are believed to be caused by sand or other third bodies in wheel-rail contact.

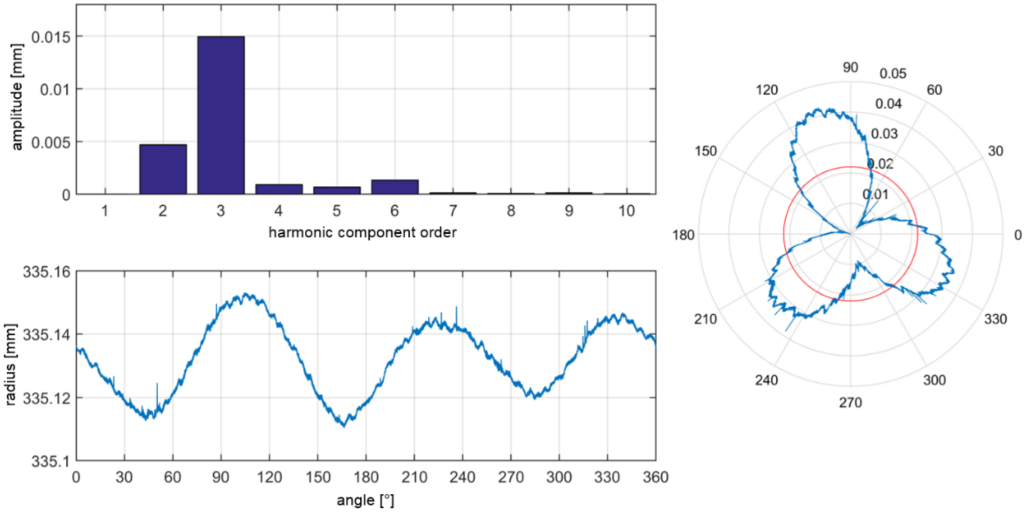

Fig. 8. Graphical representation of the measurement results of the new Düewag GT8 wheel

Figure 8 shows a graphical representation of the measurement results of the new Düewag GT8 wheel. The polar graph shows the correlation between the value of the deviation and the angular coordinate. The red circle is the mean value of the deviation, i.e. it shows the position of the individual deviations relative to the diameter of the wheel being measured. Here, polygonization of the outline of the new rim is clearly visible, and the shape of it resembles a three-leaf clover. The values for OOR irregularities are small, but measurable. Irregularities in the rolling radius centered themselves around the second and third harmonic components, with the highest value for the latter. Components 1 and 7-10 are almost non-existent. The signal appears smoother for shorter waves of irregularities and is much less jagged than on the new Tramino S105p wheel. The spread of values was about 0.04 mm.

Figure 9 shows a graphical representation of the measurement results of the worn Düewag GT8 wheel. The polar graph shows the correlation between the value of the deviation and the angular coordinate. The red circle is the mean value of the deviation, i.e. it shows the position of the individual deviations relative to the diameter of the wheel being measured.

Compared to the new wheel, the worn wheel has a much less regular surface. The three-leaf clover is deformed – one "leaf" has greatly increased in size, as visible through the appearance of the first component of the spectrum. The radius is much more jagged, and the values of higher harmonic components have also increased. It can be assumed that rolling noise emission is intensified by the process of wearing out wheels. The spread of values was about 0.15 mm.

Figure 10 shows a graphical representation of the measurement results of the new Konstal 105Na wheel. The polar graph shows the correlation between the value of the deviation and the angular coordinate. The red circle is the mean value of the deviation, i.e. it shows the position of the individual deviations relative to the diameter of the wheel being measured.

The prevailing trend in the case of the Konstal 105Na wheels was the tendency for ovalization – the second harmonic component had the highest value, whereas the third component had the second highest value. Here, some of the higher components were already visible on the new wheel. The spread of values was approximately 0.05 mm. Compared to the new wheels on the other trams, the Konstal 105Na wheel was characterized by slightly smaller amplitudes of the OOR irregularities.

Figure 11 shows a graphical representation of the measurement results of the used Konstal 105Na wheel.

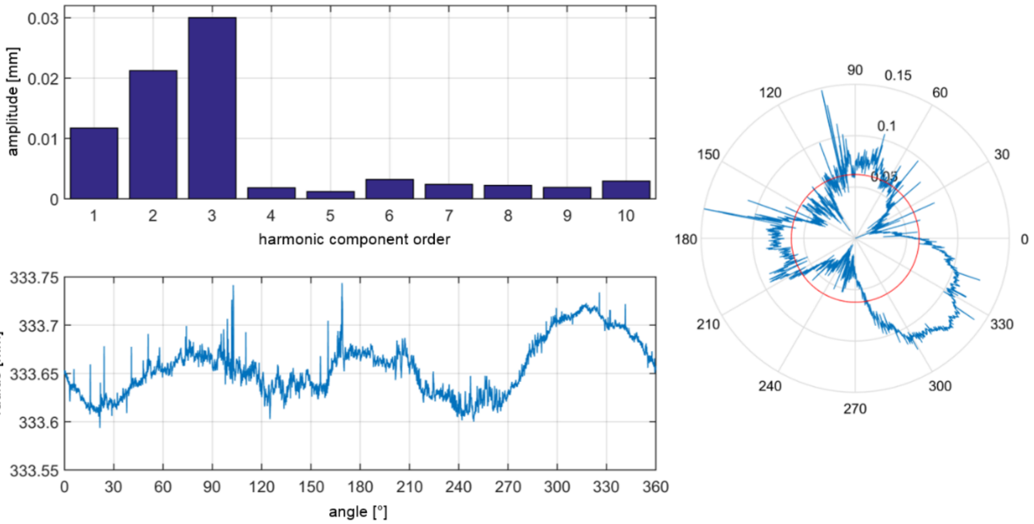

Fig. 9. Graphical representation of the measurement results of the used Düewag GT8 wheel

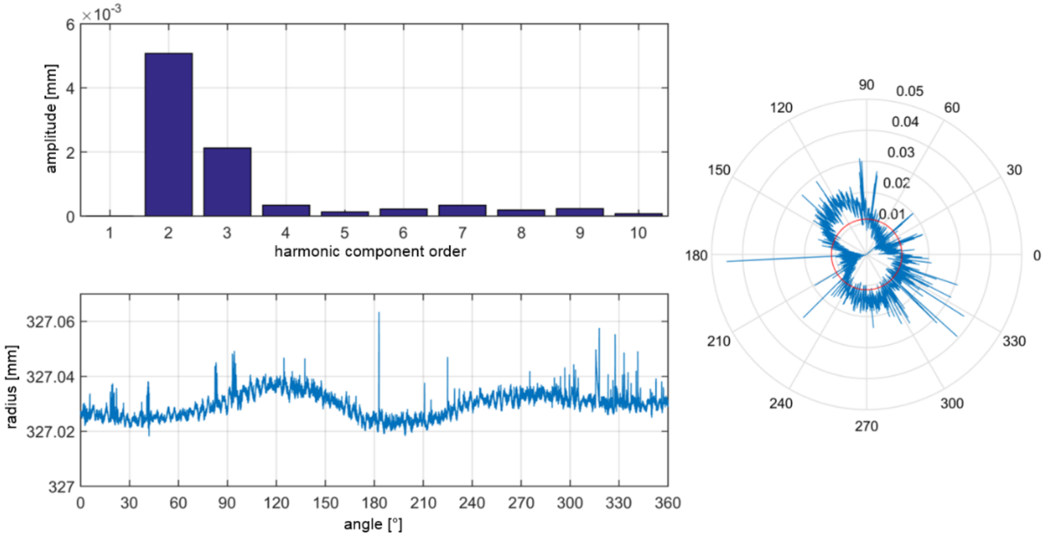

Fig. 10. Graphical representation of the measurement results of the new Konstal 105Na wheel

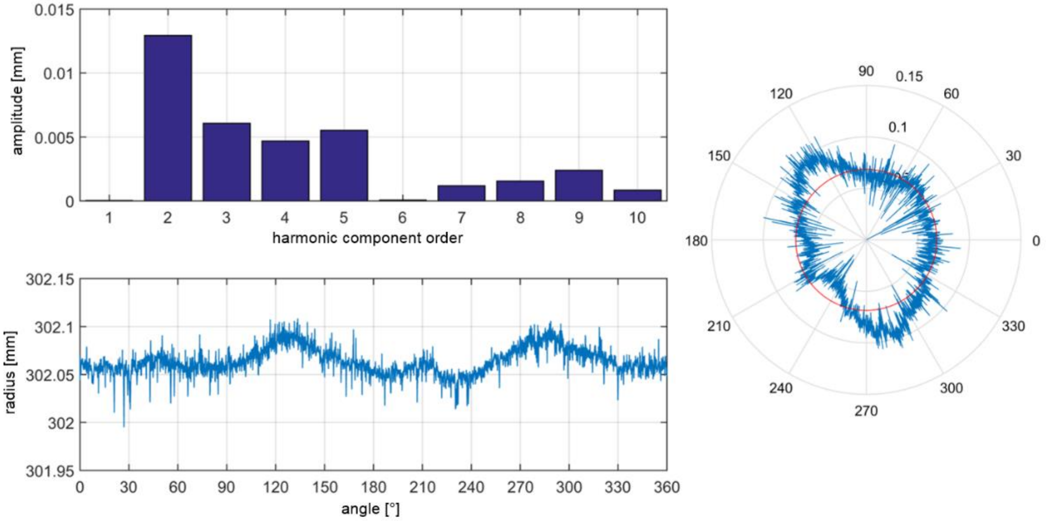

Fig. 11. Graphical representation of the measurement results of the used Konstal 105Na wheel

The polar graph shows the correlation between the value of the deviation and the angular coordinate. The red circle is the mean value of the deviation, i.e. it shows the position of the individual deviations relative to the diameter of the wheel being measured. Relative to the new wheel, the used wheel demonstrated higher amplitudes of OOR irregularities. There was also a higher amount of irregularities for higher harmonic components. The trace of the rolling radius as a function of the angle of rotation is much more uneven than that of a new wheel from the same vehicle. The spread of rolling radius values was approximately 0.12 mm.

Next, the standard deviations for the radii of the wheels were calculated, and presented in Figure 12.

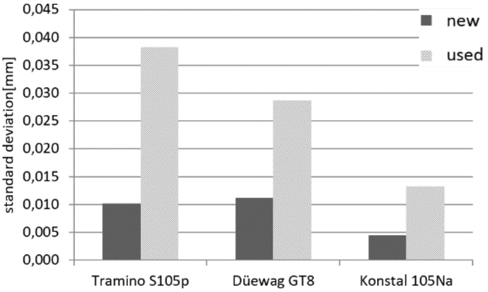

Fig. 12. Comparison of standard deviation values of rolling radii between the examined wheels

From the above, it is clear that the standard deviations for each vehicle were higher for the used wheels, with increments in the range of 160-280%. Undoubtedly, worn wheels become far more uneven at short wavelengths (higher harmonic components), which is associated with an increase in the roughness of the surface. This phenomenon is disadvantageous due to the intensification of vibroacoustic effects and likelihood of rolling contact fatigue.

5. Summary

In this paper, the current state of knowledge on tram wheels with rolling radius irregularities is presented. The following conclusions can be drawn from the summary of the research carried out above. OOR wheels create vibrations in the vehicle-wheel system with one or more component frequencies. Intensified dynamic interactions between the wheel and the rail can lead to damage of vehicle and track components. They are also a source of vibroacoustic emissions, which significantly increase the noise levels around moving rail vehicles. OOR irregularities can occur due to material defects, rapid braking or acceleration, and errors or inaccuracies during the machining of the wheels. Even small OOR irregularities can quickly increase in size, greatly intensifying the dynamic impact of the wheel on the rail. Irregularities of OOR wheels can cause them to bounce on the track and momentarily lose traction. The impact of variable loads can cause fatigue of the materials in the wheel set and other components. The dynamic loads caused by flat spots or polygonization on the rolling surface increase with their size. In most scientific papers, the dynamic effects generated by OOR wheels are proportional to the driving speed, whereas in one paper, this tendency is reversed (Martinez-Casas et al., 2015). Therefore, verification of this phenomenon is necessary. A flat area can cause up to over three times greater vertical force during wheel-rail contact. These impacts are much more intense while driving in a curve than on tangent track. While driving in a curve, the wheelsets (with flat spots) may experience different lateral forces amplifications. A higher value was occurred for the outer wheel due to a larger angle of wheel-rail contact. It was also discovered that the use of a rigid model resulted in a 20% overestimation of wheel-rail force values. The OOR irregularities become smaller as the harmonic component order of the wheel radius increases. This paper also presents the results of OOR measurements of new and used wheels. Despite the lack of visible wear, new tram wheels demonstrate very small, but measurable irregularities of the shape of the rolling circle. These irregularities are the result of the adopted technology of production (including machining) of wheel rims. The radii of new wheels often adopt lower harmonic components, usually becoming ovalized or triangularized. All the new wheels did not show the first harmonic component. As the wheels become more worn, the harmonic components of the higher orders increase, the rolling radii become more irregular, and the rolling surface becomes rougher (surface roughness). The spread of rolling radii for new wheels was about 0.04-0.06 mm, while for worn wheels it was 0.12-0.18 mm. The polygonization amplitude of new wheels increases with use, while maintaining a similar shape.

During further stages of research on phenomena related to OOR wheels, simulations will be carried out using the defined rolling radii of the wheels. Cases of flat areas on wheels will also be investigated to determine their impact on the quality of work between the track and tram wheel. The results will be described in separate paper.

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