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A CONTRIBUTION TO RESEARCH ON THE CAUSE OF AXLE ASSEMBLY EXPANSIONS OF EXPLOITED FREIGHT WAGONS

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Professional paper

A railway wheel, together with an axle, is one of the crucial parts that support the safe operation of freight wagons. In exploitation the wheels of freight cars are exposed to high heat warmings causing stresses and possible mechanical failures due to wear and geometric distance, especially when it runs directly over the break shoes. This paper gives an overview of the research on the cause of axle assembly expansions of Croatian Railways' freight wagons. The results of the research show that the widening of the wheel distance outside the tolerant limits depends on the residual stresses within the wheels themselves, and on the diameter of the wheels. Multiple regression analysis has shown to be the optimal statistical method for linking these phenomena. By analysing malfunctions concerning wheel expansions on train wagon series, a series with most frequent malfunctions has been singled out, while the main cause of these malfunctions is the manufacturer of wheel equipment A.

Keywords: *axle assembly, residual stress, malfunction frequency*

Prilog istraživanju uzroka proširenja osovinskih sklopova vagona u održavanju

Stručni članak

Željeznički kotač je zajedno s osovinom jedan od kritičnih dijelova koji su neophodni sigurnom pogonu teretnih vagona. U eksploataciji su kotači teretnih vagona izloženi velikim toplinskim zagrijavanjima koja su uzrok naprezanjima i mogućem mehaničkom lomu te geometrijskim trošenjima uslijed kočenja, posebno kad se ono izvodi izravno preko kočnih papuča. Ovaj rad daje prikaz rezultata istraživanja uzroka proširenja osovinskih sklopova vagona Hrvatskih željeznica. Rezultati pokazuju da proširenja razmaka kotača izvan dopuštenih granica ovise jednim dijelom o zaostalim vlačnim naprezanjima u samim kotačima te o promjeru kotača. Kao optimalna statistička metoda povezanosti ovih pojava pokazala se multiregresijska analiza. Analizirajući kvarove zbog proširenja kotača po serijama vagona, izdvojene su serije s najvećom frekvencijom kvarova, čiji je glavni uzročnik proizvođač kočne opreme A.

Ključne riječi: *osovinski sklop, zaostala naprezanja, učestalost kvarova*

1 Introduction

The name "axle assembly" corresponds to the system consisting of one axle, and two integrated wheels (Fig.1), whose function is to carry the base of the wagon and allow for its movements on the tracks. Malfunctions of certain parts of the axle assemblies during train movements can be the cause of serious breakdowns, which endanger people's physical safety and can be the cause of grave material damages. Analysis of the safety of train travels in Croatia and worldwide indicates that a significant number of malfunctions concerning technical components of the wagons are the result of axle assembly malfunction. Axle assembly is the most important part of the transportation system of Croatian Railways; not only does it represent one of the main elements which influences the wagon's motion safety, but also, due to its exposure to constant wearing, represents an element which causes significant expenses in exploitation and maintenance. Parts of axle assemblies are standardized according to UIC's (International Union of Railways) instructions based on the ORE's (Office for Research and Experiments) recommendation. Axle assemblies are a subject of standardization in view of their technical delivery conditions, and also in the view of their dimensions and shapes. There are UIC regulations concerning axle assembly standardization of Croatian Railways transportation system: 510 – 1 Exchangeability of the freight wagon's running machine and UIC 510-2 Conditions for using different diameter wheels for passenger and freight trains in international transport. Croatian Railways have the corresponding HRN standards for axle assemblies and their parts, which determine delivery conditions, as well as their shape and dimensions. Freight wagon's axle assemblies are produced according to EN 13260 standard. Aforementioned standard is also accepted for other components of the axle assembly: wheels, axles, monoblock wheels, rims and safety rings. In comparison to wheels with rims which used to be used, monoblock wheels are better as they provide:

- more safety during transport (no wheel loosening or breaking as with the wheels with rims),
- longer usage time (depending on the type of material and construction),
- lower prices,
- lower weight of the wheels themselves in comparison to the ones with rims [1].

The diameter of the new wheel is 920 mm, while the diameter of its last deterioration point is 850 mm.

The bearing capacity of one axle assembly is from 20 to 22 tons. Fig. 1 shows axle assembly with medium diameter of wheels and rail gauge.

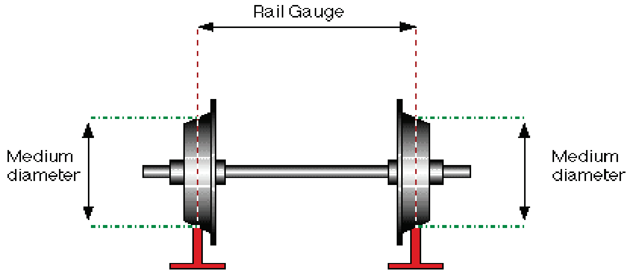

Figure 1 Axle assembly [1]

2 The load of exploited wagon's axle assemblies

The safety of train transport essentially depends on the reliability of axle assemblies, which is characterized by its capability to work in complex exploitative conditions without malfunctions. Reliability depends on the qualitative parameters of axle assemblies and their state of stress, which forms under the influence of active loads, and which, indirectly, causes the emergence of malfunctions. Train speed has great influence on the functioning of axle assemblies. The increase of speed brings about dynamic overloads of axle assemblies and causes high frequency vibrations to emerge on track sections with greater brittleness. The system of vertical, horizontal and brake forces, which have an effect on the axle assembly, are the cause of complex stresses of axle assemblies. The parts of assemblies which are exposed to the highest concentration of stresses are underneath the hub and on the trunnions where the rolling bearings are pressed. Therefore, malfunctions and deterioration intensity of exploited axle assemblies depend on many factors – conditions of exploitation (speed, tracks..), wagon type, chemical composition and mechanical features, axle assembly type, the type of brakes, wheel dimensions and their age, etc. The following sections give an overview of one of the axle assembly damage types (assembly expansion), which is caused by the brakes.

2.1 Braking and the appearance of residual stresses in the wheels [2]

The effectiveness of the brakes which affects the wheels is limited by the temperature of the brake parts. The amount of heat, which develops while braking in a unit of time, is the strength which the brake can provide. While braking, braking pads and wheel rings heat up the most. The strength of braking per wheel is calculated according to:

$$P=\frac{m\cdot g\cdot u\cdot v\cdot \varepsilon}{2\cdot Z_1\cdot Z}, \tag{1}$$

where m is train mass, g is gravity, u is rail tilt, v is speed, ε is speed irregularity factor, Z_1 is the number of axle assemblies per wagon and Z is the number of wagons.

Heat resistance of the wheel is the limit point to which the strength of the brake affecting the wheel must be subjected. Due to great forces influencing the wheel assembly when braking and great unit pressures, high temperatures occur as a consequence of the developed heat. If long term braking occurs, and if the brake is too strong, it could be the cause of rifts in the wheel plate. The damage on the friction surface develops as a consequence of the quick cooling of previously overheated spots. Stress states of the wagon wheels are very dependent on the processes of heating and cooling after braking with braking pads. Within the surface layers of the metal, structural changes of the material appear. Residual stresses in the quenched layer are the cause of lateral cracks which expand and can cause the wheel to crack [2]. Due to heating, wheels deform and move away from their nominal position. Practice has shown that the deformation, i.e. the offset is larger if the changes within the wheel caused by stress are larger. The decrease in the width of the wheel ring after re-profiling (turning) can change the layout and the size of the stresses, and increase the possibility of breaking the wheel [5]. This phenomenon is most visible on the Croatian Railways' freight train wagons, which have the SS brake regime (up to 120 km per hour) with sophisticated brake system (distributor valves, pressure regulating valve and measuring valves).

Figure 2 Measurement of residual stresses with DEBBIE machine [7]

2.2 Calculating residual stresses in wheel rings with ultrasonic method with DEBBIE machine (Fig. 2)

Residual stresses on the outer wheel rims are measured using the method of measuring the ultrasonic speed. This method uses the acoustic-elastic effect, which describes the effect of the elastic dilatation on the dispersion of the speed of ultrasonic waves. The layout of the residual stresses on the volume of the wheel rings is evaluated by using the double diffraction index. The relative time difference of two transverse wave expansions, one expanding radially, the other in a circumferential direction, is directly proportional to the difference in the main stresses, which exist in these two directions.

The application of ultrasonic waves and their expansion via the width of the wheel in radial and tangential directions results in this equation [5, 8]:

$$\sigma_{\tan}-\sigma_{\mathrm{rad}}=\frac{K\cdot(t_{\mathrm{rad}}-t_{\tan})}{t_{\tan}}, \tag{2}$$

where $\sigma_{\tan}$ and $\sigma_{\mathrm{rad.}}$ are main stresses in tangential and radial directions, K is the dependent material constant predicted in laboratory conditions and t is time of wave expansion in circumferential and radial directions.

The measured results in one spot represent the middle value of the difference in main stresses, which appear in the volume of the sound field of one measured spot [2].

3 Description of the research model

The following sections show the results of the research on the dependence of one cause of wheel displacement phenomena after exploitation on the effects of residual stresses and wheel diameter. With help of the software package STATISTICA, the aim was to obtain a mathematical model of the functional dependence of the input and output parameters. A model of first order multiple regression analysis was chosen, algorithms for calculating the model parameters were made, as well as the analysis of variance.

3.1 Multiple regression analysis

In most cases of research, there are several independent variables, therefore regression function has the following format:

$$Y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + \ldots + b_j \cdot X_j. \tag{3}$$

Finding regression parameters b_0, b_1, b_2,….b_j follows by minimizing the sum of square deviations:

$$\sum_{k=1}^{K} e_k{}^2 = \sum_{k=1}^{K} \left[y_k - (b_0 + b_1 \cdot X_{1k} + b_2 \cdot X_{2k} + \ldots + b_j \cdot X_{kj}) \right]^2 \to \min. \tag{4}$$

where e_k is value of deviation (k = 1, 2,…, K), y_k is value of dependent variable (k = 1, 2,…, K), b_0 is constant member, b_j is regression coefficient (j = 1, 2,…, J), x_{jk} is values of independent variables (j = 1, 2,…, J; k = 1, 2,…, K), j is number of independent variables and K is number of observations.

The aim of the analysis of the multiple regression function is to check the functioning of the model in reality. Measures for analysing regression function are:

- determining R^2 value,
- F-test, and
- Standard error.

The criteria for analysis of the regression coefficients are:

- t-value, and
- beta (β) value.

R^2 value is determined according to the equation:

$$R^2 = 1 - \frac{\sum_{k=1}^{K} e_k{}^2}{\sum_{k=1}^{K} (y_k - y_{\text{midd}})^2}. \tag{5}$$

The value of R^2 is a normed value which lies in the area between 0 and 1. The Eq. (4) clearly shows that the criterion of the smallest square, which is used in predicting the regression model, is equal to the maximizing of R^2 value. The value of R^2 is called multiple regression coefficient.

<u>F-test</u>

If there is correlation between the dependent variable Y and independent variables X_j, when hypothetically confirmed, then regression coefficients β_j must be equal to zero. For testing the regression model, a H_0 hypothesis was formed, which states that there is no dependence between the variables, and that regression coefficients are zero:

$H_0 : \beta_1 = \beta_2 = \ldots\ldots \beta_J = 0.$

F-test is used for null hypothesis (H_0) testing. For null hypothesis to be validated, it is expected that the value F is zero. F-value is calculated as follows:

$$F_{\text{emp}} = \frac{\sum_{k=1}^{K} (y_k - y_{\text{midd}})^2 / J}{\sum_{k=1}^{K} (y_k - y_{\text{midd}})^2 / (K - J - 1)}. \tag{6}$$

Where y_{midd} is mean of y_i, K is number of observations (samples) and J is number of regressors.

<u>Testing regression coefficient t-test</u>

In case that the testing of regression function with F-test occurs, but all regression coefficients are not zero, it is necessary to test all these coefficients individually. t-test is used for this according to the equation:

$$t_{\text{emp}} = \frac{b_j - \beta_j}{s_{bj}}. \tag{7}$$

Where t_{emp} is empirical, t-value of j regressor, β_j is actual (real) regression coefficient, b_j is regression coefficient of j regressor and s_{bj} is standard error of b_j.

3.2 Experiment planning and result analysis

The research was performed on 30 monoblock wheels (15 axle assemblies) of Croatian Railways' freight trains type R7T (Tab. 1), where the determined: function Y – increase of wheel distance, depends on X_1 – wheel diameter (in mm) and X_2 – value of residual stresses (in MPa). Residual stresses were measured with DEBBIE machine from MAVEX Company (Fig. 2), and, as shown in Tab. 1, each wheel's average stress was measured on a certain position of the wheel, on which the wheel distance was measured.

By applying STATISTICA software for result analysis using multiple regression method, a functional correlation linking input – output variables was determined (Eq. 8), as well as regression coefficients, and the model's applicability (adequacy) was tested. Regression coefficients were tested using the F-test and compared to Tab. 2.

Direct results show the convenience of multiple regression model for the description of the correlation between the dependent variable – wheel displacement and the two independent variables – wheel diameter and residual stresses. The equation of the model is described as:

$$Y = 15{,}175 - 0{,}0160679 \cdot X_1 + 0{,}00274351 \cdot X_2, \tag{8}$$

where Y is wheel displacement, X_1 is wheel diameter and X_2 is residual stresses.

Table 1 Results of the measured values

Number of measurements	Number of axle assembly	Residual stresses X_2 (MPa)	Wheel diameter X_1 (mm)	Wheel displacement (mm) Y	Number of measurements	Number of axle assembly	Residual stresses X_2 (MPa)	Wheel diameter X_1 (mm)	Wheel displacement Y (mm)
1	1	356	911	2	16		354	880	1,80
2		342	911	2	17	9	355	875	2,40
3	2	256	912	1	18		369	875	2,40
4		234	911	1	19	10	321	875	2,30
5	3	280	912	1	20		328	875	2,30
6		264	911	1	21	11	345	875	2,20
7	4	272	911	1	22		356	875	2,20
8		263	912	1	23	12	252	900	1,35
9	5	302	865	2	24		263	900	1,35
10		314	865	2	25	13	260	900	1,40
11	6	368	865	2	26		226	900	1,40
12		402	865	2	27	14	213	900	1,35
13	7	345	880	2	28		123	900	1,35
14		374	880	2	29	15	214	900	1,35
15	8	362	880	1,8	30		181	900	1,35

Table 2 Overview of the results of statistical analysis of data

Parameter	Estimate	Standard Error	T-Statistic	P-Value
Constant	15,175	3,24545	4,67577	0,0001
Wheel diameter	-0,0160679	0,00345289	−4,65346	0,0001
Residual stresses	0,00274351	0,000894462	3,06722	0,0049

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	5,03617	2	2,51809	39,02	0,0000
Residual	1,7425	27	0,0645369		
Total	6,77867	29			
R-squared	74,2944 %				
R-squared (adjusted for d.f.)	72,3903 %				
Standard Error of Est	0,254041				
Mean absolute error	0,203375				
Durbin – Watson statistics	0,737494 (P=0,0000)				

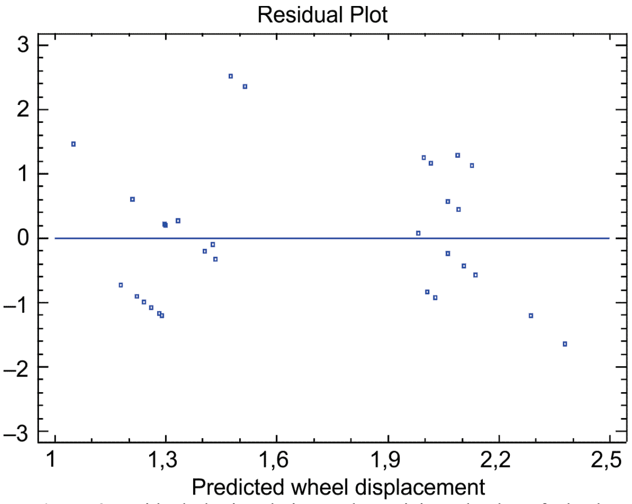

Figure 3 Residual plot in relation to the anticipated value of wheel displacement

Since P-value in the analysis of variance (ANOVA) is less than 0,05, there is a significant statistical link between the variables within 95 % reliability interval. R-squared statistics show that the model explains 74,2944 % of variabilities in the variable Wheel displacement (Y). Statistics of the adjusted R-squared show that the standard deviation is 0,254041. Mean absolute error (MAE) adding up to 0,203375, is the average value of the residuals. In determining the simplification of the model, it is noticeable that the highest P-value for an independent variable is 0,0049, which belongs to Residual stresses.

Fig. 3 shows that there is no underlying system error outside the boundaries.

3.3 Statistical overview of the frequency of wheel expansions on the series of CR's freight wagons

In order to analyse in detail the dependence of the wheel expansions on the appearance of residual stresses and the wheel diameter, Pareto diagram analysis was conducted for the frequency of the wheel expansions on the series of freight wagons which differ in the inbuilt braking systems, in the period from January 2010 to May 2012 (Fig. 4). The research has divided the freight trains according to the brake system manufacturers A, B and C, and the total number of wagons analysed was N = 750 wagons (250 wagons with brake system A, 250 wagons with brake system B, and 250 wagons with brake system C).

The results (Fig. 4) show that most frequently (61,9 %) damaged axle assemblies, due to wheel expansions, are on the wagons with brake system from the manufacturer A.

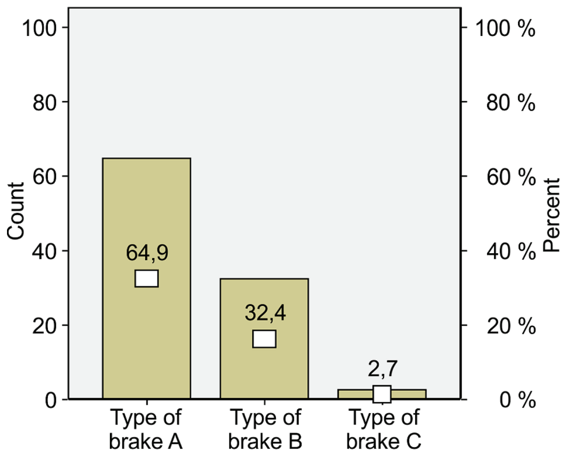

Figure 4 Pareto diagram of the frequency wheel expansion malfunctions on Croatian Railways' wagons

4 Conclusion

Based on the test results and description gained via multiple regression analysis, it can be concluded that:

- the appearance of axle assembly expansion depends on the residual stresses and wheel diameter
- by analysing the frequency of malfunctions due to expansion of axle assemblies with appearance of residual stresses (Pareto Diagram), it is found that the wagons on which the brake systems from the manufacturer A are installed are the cause of these malfunctions in 61,9 % of cases, and it is recommended that they be replaced with brake systems of higher efficiency or reconstructed.

Results of the research in this paper are of great practical value when applied to Croatian Railways as they can serve as a guideline for the owner, i.e. wagon caretaker, when ordering or buying new axle assemblies (concerning the type of wheel material of greater toughness and thermal treatment due to appearance of residual stresses), as well as adequate braking equipment (wheel strength dimensioning) in the future due to high current expenses caused by the aforementioned phenomena described in this paper.

5 References

[1] Frković, M. Uputa za održavanje osovinskih sklopova, Zagreb 2010.
[2] Vranić S. Kočenje vlakova, 1. izdanje, Tvornica željezničkih vozila Gredelj d.o.o., Zagreb, 2000.
[3] Hrvatska norma HRN EN 13262 – Oprema za željeznice – osovinski sklopovi i okretna postolja – kotači – zahtjevi za proizvod (EN 13262-2004).
[4] Backhaus, K.; Erichson, B.; Plinke, W.; Weiber, R. Multivariate Analysemethoden, Eineanwendungsorientierte Einfuhrung, 11. Auflage, Springer Berlin.
[5] Laczko, P.; Mutton, P. J. Metallurgical and NDT aspects in the management of overheated railways wheels, Materials Forum Volume 30-2006, Institute of Materials Engineering Australasia.
[6] Hrvatska norma HRN EN 13715 – Oprema za željeznice – osovinski sklopovi I okretna postolja – kotači – profil kotača (EN 13715:2006)
[7] Jemec, V.; Grum, J.; Božičko, S. Ultrasonic measurement of hoop stresses in the rim of monobloc railroad wheel, Česka společnost pro nedestruktivni zkoušeni material, 38. mezinarodni conference defektoskopie 2008, Brno 4.-6.11. 2008.
[8] Schneider, E. Ultrasonic evaluation of stresses in the rims of railroad wheels, ECNDT Konferencija, Kopenhagen, 26.-29.5.1998.
[9] ORE Frage B 169, Technische Grenzen Der Räder und Bremsklötze, Bericht Nr. 2: Auswirkunghäufiger-bremsungen auf das Eigenspannungsfeld im Radkranz, April 1989.

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