578. Shape Optimization of Mounting Disk of Railway Vehicle Measurement System

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Abstract. Nowadays special tensometric wheel pairs are used for the monitoring of wheel-rail system. In this work the task of unification of the tensometric wheel pairs and reduction of expenses required for testing is considered. The equipment allowing realization of the measurements for the monitoring of wagon or locomotive system wheel-railing using ordinary standard wheel pair is elaborated. The objective of optimization is to determine the shape of the equipment mounting disk with minimal volume constrained by specified displacement and stress levels. Dynamic excitations due to the rail irregularities and flat of wheel are taken into account. The strength calculations of the mounting disk are realized by FEM and are relatively time consuming. The shape optimization using metamodels is discussed. Procedures of metamodel building by local approximations are used. The optimal curved shape of the cross-section of the ellipsoidal mounting disc is elaborated.

Keywords: railway testing, measurement system, shape optimization, metamodel

Introduction

At present time special tensometric wheel pairs are used for the monitoring of wheel-rail system. For each type of rolling stock these wheel pairs must fit vehicle wheel wearing condition, diameter and bearing box connection type. Using and delivering of the tensometric wheel pairs are expensive and take a lot of time for preparing of strength – dynamics tests. In this work removable equipment for monitoring is proposed to mount on the ordinary wheel pairs. Monitoring wireless system [1, 2] for 80 tons wagon (freight car) is taken for prototype. The movable part of equipment (Fig. 1) consists of removable disk, two transmitters and transmitting antenna as well as strain gauges bonded to the wheel at defined places. Removable disk is fixedly attached to wheel pair axis. Circular transmitting antenna and two transmitters are mounted on outside of the disk.

Removable equipment must be lightweight to minimize distortions of measurements and at the same time it must possess appropriate durability. During testing dynamical loads that are induced by rail joints, railroad switches and other irregularities as well as due to defects of wheel geometry are transmitted from wheel pairs to removable disk, which is rigidly mounted on the wheelset axis. Therefore shape optimization of the mounting disk that is the main large-weight part of equipment is very important to reduce its total weight.

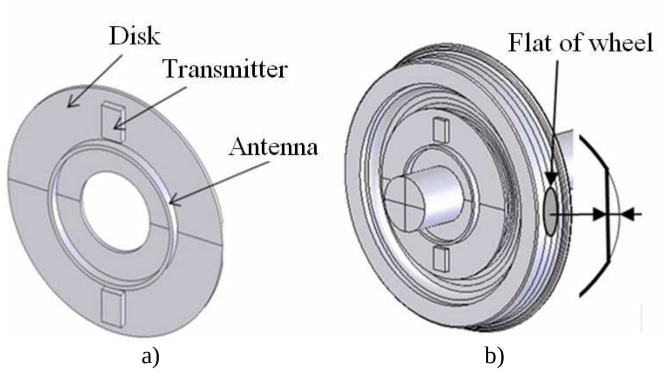


Fig. 1. a) Removable disc with elements of measurement system and b) its mounting place

Loads acting on wheel pairs

The main loads are acting in vertical direction and are induced by railroad irregularities and wheel defects in the wheel-railroad contact. The removable disk sustains all loads from wheel pair because it is rigidly fastened. Strength of the removable disk is calculated for maximal possible loading. For example in the case when the wheel pair have 2 mm flat of wheel (Fig. 1b), the loaded and empty wagon wheelsets undergo to different loads in vertical direction at different velocities (see Table. 1) [3]. For empty wagon the maximal load is at velocity 5 m/s, but for the loaded wagon at 10 m/s. Strength of the removable disk will be analyzed with maximal vertical load – 620.6 kN for two cases of orientation of the transmitters - horizontal and vertical when the wheel pair acceleration can reach 12 g (the gravitational acceleration g = 9.81 m/s^2 is taken into account).

Table 1. Load versus velocity of wagon [3]

Velocity of wagon m/s	Maximal load in moment of shock, kN	
	Empty wagon	Loaded wagon
Static load	22.8	104.5
1	136.1	251.3
2	170.2	316.4
5	297.8	367.2
10	271.3	620.6
20	276.6	604.9

Strength of the disk under centrifugal load will be also analyzed at maximal vehicle velocity 200 km/h (wheel angular velocity = 116.98 rad/s). In this case the disk is considered as new without wear on riding circle.

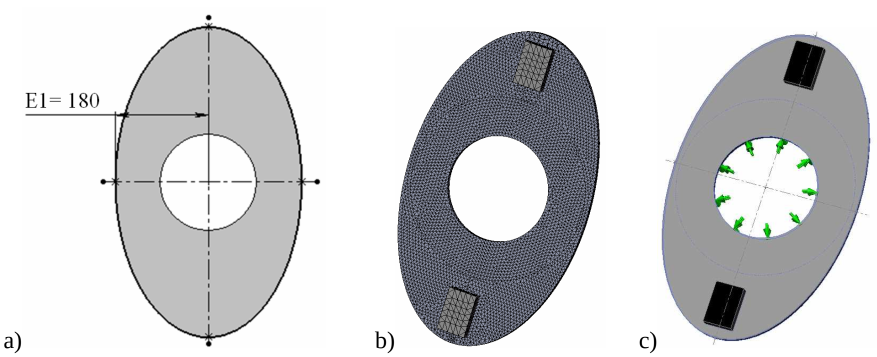
Moreover, frequency analysis was performed to determine natural frequencies of wheel pair and evaluate possible resonance in the case of flat of wheel. Obtained results demonstrate that excitation frequencies at velocities of operating conditions are significantly smaller than fundamental frequency.

Disk model for strength calculation

The geometrical model of the disk is constructed by means of SolidWorks [4]. It takes into account the shape, size and material of the disk and transmitters (dimensions - 20x55x80 mm, mass - 0.1 kg). The transmitting antenna (Fig. 1) is removed from the calculation model because it has small dimensions and is a lightweight component. The calculation model does not consider fastening holes and fastening elements either. The transmitting antenna operates stable if its displacement in axial direction is less than 2 mm [1]. This constraint is taken into account in the next calculations.

The strength calculations are performed by SolidWorks Simulation (alias CosmosWorks) [5]. Firstly, the shape of removable disk (radius R = 300 mm and thickness b = 10 mm) is changed to ellipse with semi-major axis length 300 mm and semi-minor axis $E1$ (Fig. 2a) by simple size optimization of $E1$. This shape is convenient for the equipment mounting purposes and is taken for initial design.

FE mesh is generated with the second order tetrahedral solid elements and is generated to obtain high accuracy results (Fig. 2b). It consists of about 51000 elements with 86000 nodes (258000 DOF).



a) b) c)

Fig. 2. a) Ellipsoidal disk; b) Computational finite element mesh of the model; c) Scheme of disk fastening

Displacement of removable disk is restrained on its cylindrical face as fixed (Fig. 2c).

Material of the disk is aluminum alloy (1060 H12) with elastic modulus E= 69000 MPa, Poisson's ratio ν = 0.33, mass density ρ = 2700 kg/m^3 and yield strength σ_y = 27.5742 MPa. The material's ultimate fatigue resistance is calculated as [6]:

$$\sigma_{-1} = 0.4 \cdot \sigma_y \tag{1}$$

So stresses must be less than $\sigma_{-1} = 11.0297$ MPa. Additionally, the value of factor of safety FOS = 2.75 is assumed to be confident that the disk will be durable in any worst-case situation [6]. The acceptable stress in the disk material is reduced to $\sigma_{\max} = 4$ MPa. Von Misses yield stress criterion is used for all strength calculations:

$$\sigma_{vonMises} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}}\ ; \tag{2}$$

where $\sigma_1, \sigma_2, \sigma_3$ are principal stresses.

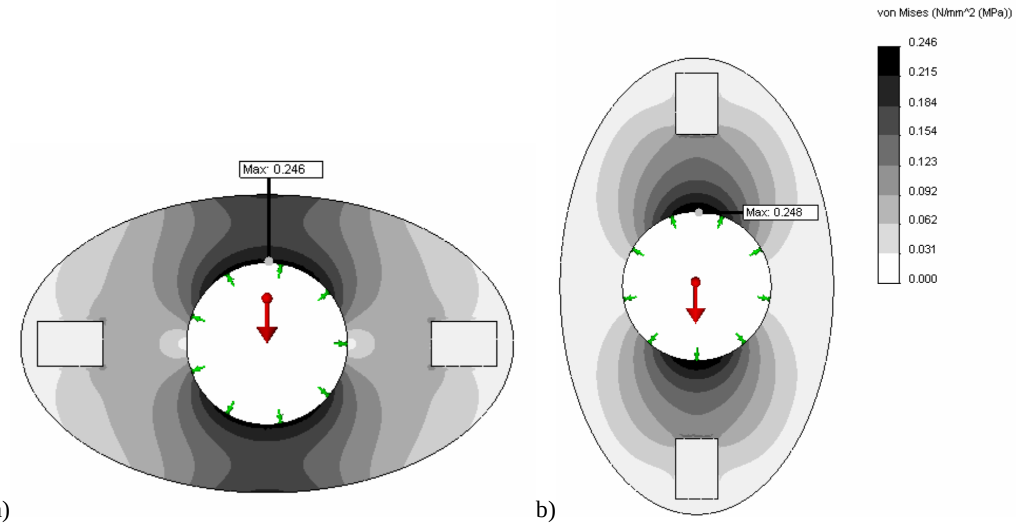
Thereby the von Misses stress at any point of the disk should be less than acceptable stress:

$$\sigma_{vonMises} < \sigma_{\max} \tag{3}$$

Stresses in disk of initial design

Three variants of stressed state of the disk are analyzed, i.e., from loads due to flat of wheel in two cases of the disk orientation: when major axis of ellipse is vertical and horizontal as well as from centrifugal loads.

There are considered loaded wagon with maximal loading in moment of shock that occur at velocity of 10 m/s (Table 1). Maximal stresses in moment of shock (acceleration a =119.3 m/s^2) are presented in Fig. 3. As we can observe, values of maximal stress levels for both orientations of the disk are very similar.



a) b)

Fig. 3. Von Misses stresses distribution in initial design disk for a) horizontal and b) vertical orientation

The results for stressed state of initial design of the disk from centrifugal load are depicted in Fig. 4. Maximal von Misses stress in the disk from centrifugal load is at least 12 times greater than in the case of loading from flat of wheel.

Shape optimization of cross-section of the ellipsoidal disk

The shape of cross-section of the disk is optimized taking into account only centrifugal load. Design restrictions allow modification of disk cross-section shape only at one side and in radial direction in the range of 150-300 mm from ellipse center. Section of the disk at radial distance 0-150 mm has constant thickness b=10 mm. Three methods are used to define cross-section shape (Fig. 5): a) with NURB spline [7] knot points, b) with NURBS polygon points and c) with points that are connected with straight lines. Four parameters are stated to define the shape. Parameters are varied in the following ranges: $4 \le X1 \le 10$; $4 \le X2 \le 10$; $5 \le X3 \le 12$; $3 \le X4 \le 5$ for variants "a", "c" and $3 \le X1 \le 10$; $0.5 \le X2 \le 20$; $5 \le X3 \le 25$; $2 \le X4 \le 5$ for "b". The design of experiments is calculated with MSD (mean-square distance) criterion [8] for 4 factors and 70 trial points by EDAOpt - software for design of experiments, approximation and optimization developed in Riga Technical University.

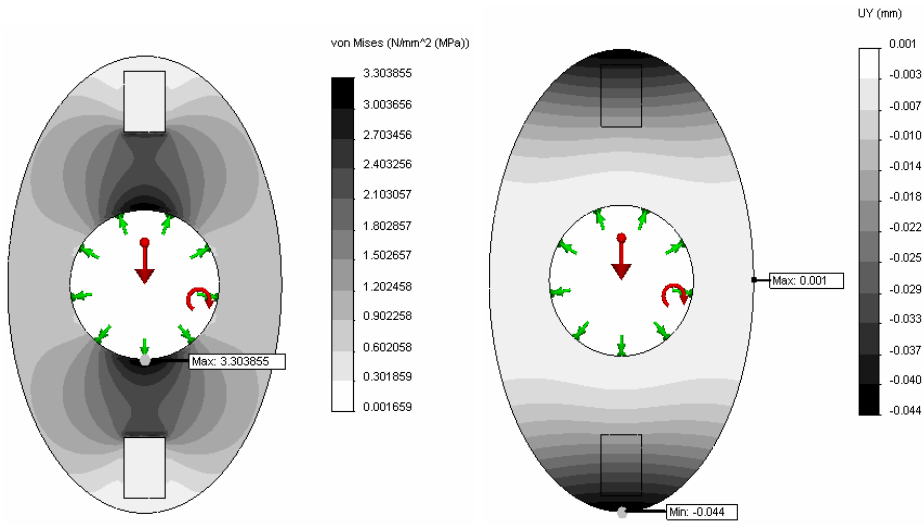


Fig. 4. a) Von Misses stresses distribution in initial design disk from centrifugal loads; b) disk's displacements in axial direction

So the 70 strength studies are calculated for each of considered method. SolidWorks Simulation results (volume, maximal von Misses stress, axial displacement of the disk etc.) are entered into EDAOpt for approximation and subsequent global search. For example, for approximation of response y by quadratic polynomial the following expression [8] is used:

$$\hat{y} = \beta_0 + \sum_{i=1}^{d} \beta_i x_i + \sum_{i=1}^{d-1} \sum_{j=i+1}^{d} \beta_{ij} x_i x_j + \sum_{i=1}^{d} \beta_{ij} x_i^{\ 2} + \varepsilon \tag{4}$$

where there are d variables $x_1,\ldots, x_d$, $L=(d+1)(d+2)/2$ unknown coefficients β and the errors ε are assumed independent with zero mean and constant variance σ^2. In case of local approximation coefficients $\boldsymbol{\beta}=(\beta_1, \beta_2, \beta_3,\ldots, \beta_L)$ depend on point x_0 where prediction is calculated and are obtained by means of weighted least squares method:

$$\beta = \arg\min_{\beta} \sum_{j \in N_x} w(x_0 - x_j) \times (y_j - \hat{y}(x_j))^2 \tag{5}$$

where the significance of neighboring points in the set N_x is taken into account by Gaussian kernel:

$$w(u) = \exp(-\alpha u^2) \tag{6}$$

where u is Euclidian distance from x_0 to current point and α is the coefficient that characterizes significance.

Quality of approximation is estimated by cross-validation relative error:

$$\sigma_{Xrel} = 100\% \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_{-i}(x_i) - y_i)^2}}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{7}$$

where root mean squared prediction error stands in numerator and mean square deviation of response from its average value stands in denominator, n is a number of confirmation points and $\sum_{i=1}^{n}\hat{y}_{-j}(x_i)$ denotes sum of responses calculated without taking into account j-th point. Leave one out cross-validation method is used for calculating of (7). The global random search procedure [10] realized in EDAOpt is used for optimization.

Some characteristics of optimization and approximation are listed in Table 2. Results of variants "a" and "b" are obtained with second order local polynomial approximation. Third order local polynomial approximation is used for variant "c". Gaussian kernel coefficient α was varied for least value of cross-validation error (7).

Table 2. Quantitative data of approximation and shape optimization of the ellipsoidal disk cross section

Variant	α	Approximation's σ_{Xrel} [%]		Volume v [mm^3]			Maximal von Misses stress $\sigma_{vonMises}$ [MPa]		
		$\sigma_{vonMises}$	v	Predicted	Real	Error [%]	Predicted	Real	Error [%]
a	6	20.56	0.06	1003944	1003891	0.005	3.9999	3.833816	4.33
b	3	40.28	2.03	923421	921740	0.018	3.9999	4.200354	4.77
c	4	10.93	0.00	946180	946173	0.001	3.9998	4.125750	3.05
d	-	-	-	-	1394900	-	-	3.3	-

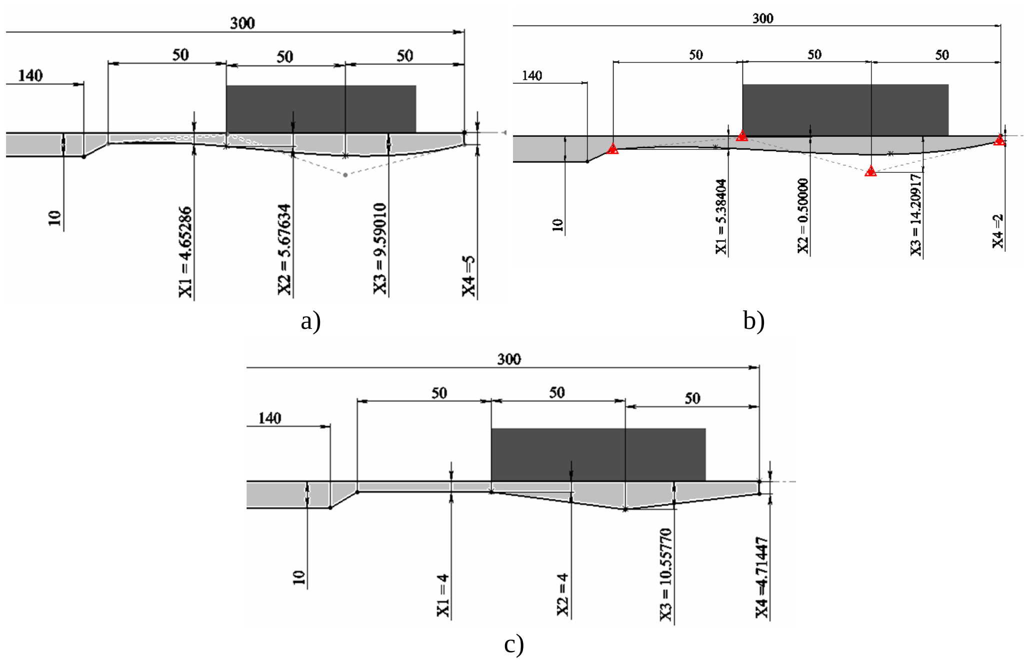


Fig. 5. Results of optimization of ellipsoidal disk. Shape of cross-section is defined by a) NURBS knot points, b) NURBS polygon points, c) points that are connected with straight lines

The obtained metamodels are used for optimization of factors. The ellipsoidal disk volume is minimized by taking into account the specified constraints on displacement and stress level. The obtained shapes are presented in Fig. 5. Table 2 indicates that the best results are obtained for variant “b” (Fig. 6), where the volume is lower by 8.2 % in comparison to variant “a” and by 2.6 % with respect to “c”. All 3 variants give significant advantage in volume (28.1 – 33.9 %), when comparing to variant “d”- the initial shape design with constant 10 mm thickness.

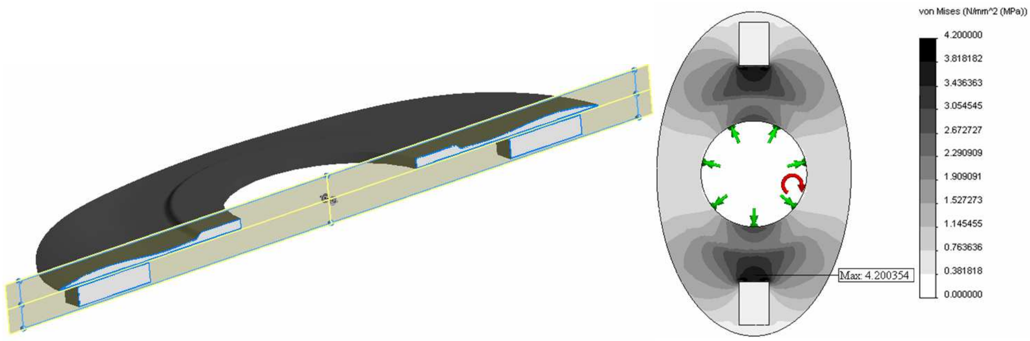


Fig. 6. Half of 3D model of optimal shape disk and real von Misses stresses distribution in it

Conclusions

The proposed equipment enables application of standard wheel pair with removable measurement equipment as tensometric wheel pair that considerably reduce material and time expenses required for preparation of testing. By means of size and shape optimization the total volume of the mounting disk of railway vehicle measurement system is reduced by ~64 % in comparison with initial design. The method based on NURBS polygon points provides the shape with at least 3% better objective (volume) than other used methods.

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