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Theoretical and experimental determination of the force generated by the pressure of the friction pad in the brake disc of railway vehicles

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ABSTRACT

The braking systems of railway vehicles, and in particular the mechanical braking system, contain component elements that, during this regime, are in direct contact by friction (shoe - wheel, friction lining - brake disc). The phenomenon of friction, in the case of braking of railway vehicles - dry friction, leads to wear of the friction coupling elements, which often occurs unevenly, with negative effects on driving safety. In this work the results of the theoretical and experimental research obtained using the disc brake are presented: the distance from the center of mass of the brake disc to which the normal force must be applied to obtain a uniform wear of the friction lining; normal and tangential forces; the coefficient of friction between the elements of the disc brake friction coupling. In order to determine experimentally the forces generated by the pressure of the friction lining on the brake disc, three identical flexible elements were proposed in the work, to a suitable shape for the braking regime, which were equipped with a tensiometer as a transducer and formed a force cell mounted on a plate. Thus, through this force cell, it was possible to experimentally determine and synthetically present (tables) certain deviations and manufacturing defects of the disc brake wheelhouse used in classic and high-speed railway vehicles.

Keywords: force transducer, pad friction, brake disc, force cell.

1. INTRODUCTION

The disk brake was first mounted on fast trains, then on trains designed for the suburban and urban traffic both on passenger and freight cars running at speeds higher than 120 km/h for the following reasons:

1. The braking power margin of the shoe-brake has been surpassed mainly at high speeds;
2. The maintenance of the disk brake is cheaper;
3. The comfort of the journey is increased;
4. The variation of the friction index against the specific speed and pressure is lower;

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5. The pressure forces of the friction lining on the disk brake are smaller as compared to those occurring at the shoe-brake and therefore smaller brake cylinders and simpler brake linkages can be used.

The disk brake theoretical calculus

An important value for the calculus of the disk brake is the *mean friction radius* (Fig.1), (Bocîi, L.S, 2006), (Copaci, I., Velescu I., 1988; ERRI B 126, 1985).

Further on, the braking moment has to be determined. At a symmetrical load and an even distribution of pressure all over the surface of the friction pad, the braking moment of the disc is given by the relation (1)

$$M = F_S \cdot r \cdot \mu_S \quad [\mathrm{Nm}] \tag{1}$$

where:

F_s – the pressure force of the pad on the disk, [N];

r - the mean radius of the brake disk;

μ_s - the friction index of the friction pad on the brake disk.

The pressure between the disk and pad is considered to be evenly distributed only on a narrow area of its surface. Due to the great differences of speed between the points on the grey iron disk, located closer or farther away from the wheel axis, the friction lining wears off unevenly if the pressure of the lining on the disk applies to its load center. In this case, pressures occur between the pad and the disk, which are smaller or bigger depending whether the areas are closer or farther away from the wheel axis. An even wear off of the friction linings is ensured if the pressure force applies far from the wheel axis (Fig.1.)

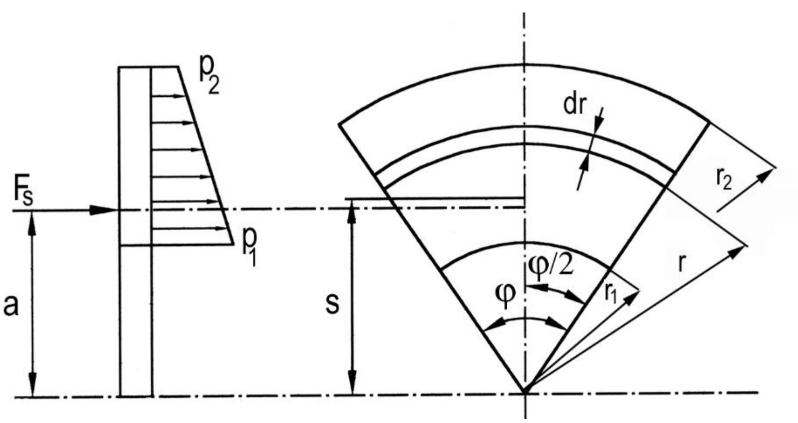

Figure 1. Calculus of the disk brake is the mean friction radius

Fig.1 also shows that in the case of an asymmetrical clamping force F_s, on the upper side of the disk, to which relatively higher speeds correspond, minimal pressures p_2 occur, while in the lower part of the disk, lower speeds and maximum pressures p_1 occur. The wear of the pads is due to the friction on the friction surfaces of the brake disc. The condition required to ensure uniform wear of the friction lining is given in equation (2):

$$p \cdot v = k_1 = \mathrm{const.} \tag{2}$$

where: p- the pressure between the friction pad and the brake disk in the surface element considered [N/cm^2];

v – the relative speed between the friction pad and the brake disk in the considered spot [m/s];

k_1 – proportionality constant.

The relative speed between the friction pad and the brake disc of radius r is in a proportionality relationship represented by equation (3):

$$v = r \cdot k_2 \tag{3}$$

k_2 – proportionality constant.

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Given this relation, condition (2) may be written by equation (4) or (5):

$$p \cdot r = k = const. \tag{4}$$

or

$$p = \frac{k}{r} \tag{5}$$

k – proportionality constant

It can be noticed from Figure 1 that the pressure of the friction pad on the brake disk can be determined by subsuming the elementary forces F_s, expression (6):

$$F_s = \int_{r_1}^{r_2} p \cdot \varphi \cdot r \cdot dr = \int_{r_1}^{r_2} \frac{k}{r} \cdot \varphi \cdot r \cdot dr = \int_{r_1}^{r_2} k \cdot \varphi \cdot dr = k \cdot \varphi \cdot (r_2 - r_1) \tag{6}$$

Starting out from the equivalence of the moment of asymmetrical forces F_s to the moment of clamping forces symmetrically applied F on arm s, the relation (7) is obtained:

$$F_s \cdot a = F \cdot s = \int_{r_1}^{r_2} p \cdot r \cdot s \cdot \varphi \cdot dr \tag{7}$$

where:
a - the distance, from the brake disk centre at which force F_s has to apply so as to generate an approximately even wear of the friction pad (to be determined).

Considering the following expression (8) of the disk arc load center:

$$s = \frac{r \cdot \sin \frac{\varphi}{2}}{\frac{\varphi}{2}}, \tag{8}$$

and relation (5), from the equivalence of the moments the relation (9) is obtained:

$$F_s \cdot a = \int_{r_1}^{r_2} p \cdot r \cdot r \cdot \frac{\sin \frac{\varphi}{2}}{\frac{\varphi}{2}} \cdot \varphi \cdot dr = \int_{r_1}^{r_2} \frac{k}{r} \cdot r \cdot r \cdot \frac{\sin \frac{\varphi}{2}}{\frac{\varphi}{2}} \cdot \varphi \cdot dr = \int_{r_1}^{r_2} k \cdot 2 \cdot r \cdot \sin \frac{\varphi}{2} \cdot dr = k \cdot \sin \frac{\varphi}{2} \cdot \left(r_2^2 - r_1^2\right) \tag{9}$$

If the expression of the force Fs of the relation (6) is replaced in the relation (9), the relation (10) represents the distance a:

$$k \cdot \varphi \cdot (r_2 - r_1) \cdot a = k \cdot \sin \frac{\varphi}{2} \cdot \left(r_2^2 - r_1^2\right) \Rightarrow a = \frac{1}{\varphi} \quad \sin \frac{\varphi}{2} \cdot (r_2 + r_1) \tag{10}$$

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This relation (10),), (Bocîi, L.S, 2011), (ERRI B 126, 1985; UIC 546; UIC 547), represents the distance, from the brake disk center at which force F_s *has to apply so as to generate an approximately even wear of the friction pad.*

2. MATERIALS AND METHODS

2.1. Description of the force cell

The task of the force cell is to determine experimentally not only the pressure distribution of the friction pad on the brake disk by measuring the force in 3 points located at the marginal points of the area, but also the determination of the force of the friction pad on the disk by subsuming the three component forces.

The problem is solved via the production of three flexible, identical and adequately shaped elements provided with a tensiometer and fitted on a plate, thus forming a force cell capable of fulfilling the aforementioned task.

Further on, the paper illustrates an example of a force cell (Figures 2-4), (Copaci, I., Velescu I., 1988), (Velescu I., et al. 2002; Bocîi, L.S, 2002):

- A view of the force cell (Figure 2);
- The location of the electrical variable-resistance transducers on the flexible element (Figure 3);
- The connection of the electrical variable-resistance transducers onto the electrical balance (Figure 4).

The force cell determining the pressure and pressure distribution of the friction pads on the brake disk consists of a *plate* 1 that has a shape similar to the friction pad used for the respective brake and *flexible elements* 2 adequately shaped, fitted with electrical variable-resistance transducers T1……T4 *and* displaying also *supports* 3 which during braking lean against the brake disk.

The measuring of the component forces in points A, B and C, i.e. : F_A, F_B, F_C is done by determining the signal obtained at three electrical balances made of electrical variable-resistance transducers connected as per Figure 4, for each flexible element and for each measured component force respectively.

If a suitable shape is chosen for the plate and the flexible elements, these elements assembled together form a force cell which can be placed instead of the existing friction pad, thus allowing for experimental determinations of the braking pressure and of its distribution on the surface of the friction pad under steady- state conditions.

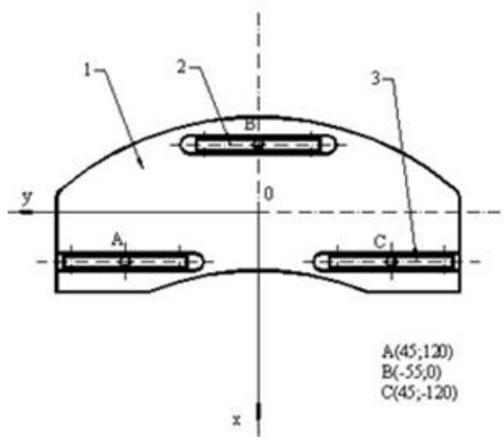

Figure 2. Force cell view

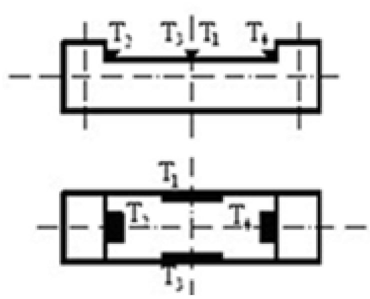

Figure 3. The location of the transducers in the flexible element

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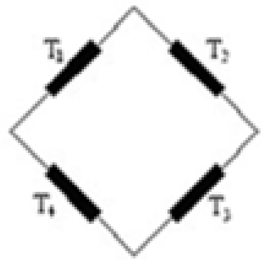

Figure 4. The connection of the electrical variable resistance transducers on to the electrical balance

The force cell designed for the determination of the pressure distribution of the friction pad on to the brake disk has the following advantages:

- It allows for the measurement of the pressure exerted by the friction pad on the disk of the disk brake;
- It allows for the measurement and determination of the pressure distribution of the friction pad on the brake disk in the three points considered;
- Depending on the values of the pressure in the three points considered , it can be established whether the pressure is evenly distributed, and the necessary technical measures can be taken in order to generate an equalizing of the values of the three components of the friction pad pressure;
- The shape of the force cell allows for an easy mounting/dismounting, observing the same technology as the one used for the mounting/dismounting of the friction pad.

2.2. Experimental measurements

Using the existing force cells, experimental tests have been carried out upon various passenger car bogies, currently running on the railroads in Greece. These bogies have been provided with disk brakes driven by two 254 mm cylinders.

The measurement chain was composed of 4 force cells connected to UMK 10 switch boxes and a KWS 3050 Hottinger Baldwin Messtechnik amplifier. The supply of the two bogie brake cylinders has been made via a KEs Dü 21C/1.27 air sparger and a mobile braking stand fitted with a KD2 (Knorr D2) valve tap. The trial pressure was of 38 N/cm^2.

3. RESULTS

The results of the experiments are shown in Table 1 for the bogie that was used in traffic and in Table 2 for the same bogie after the application of the measures designed to make the necessary corrections for the pressure distribution, so as to maintain an uneven wear below22%. To fulfill this aim it is necessary that $y_F < 5.7$ mm and $x_F < 2.33$ mm.

Values x_F and y_F represent the coordinates of the point in which the resultant pressure applies against the reference system. The denotations in the tables stand for:

- F_A, F_B, F_C - the determined forces in point A,B,C;
- F_T the total pressure force on the friction lining;
- I and E – internal and external positioning of the force cell to the brake disk.

Table 1. The results of the experiments for the bogie that was used in traffic

Bogie no.	Shaft neck	Pick-up	F_A [daN]	F_B [daN]	F_C [daN]	F_T [daN]	x_F [mm]	y_F [mm]
0081/1980	1	I	562	689	631	1882	8,39	-4,39
		E	216	931	638	1785	-7,15	-28,36
	2	I	530	863	463	1856	-1,49	4,33
		E	390	648	781	1819	9,37	-25,79
	3	I	505	992	340	1837	-9,00	10,77
		E	633	718	478	1829	5,74	10,16
	4	I	74	687	688	1449	-2,28	-50,84
		E	676	825	155	1656	-4,81	37,75

(1, 2, 3, 4 – the shaft neck number of the two axles of the bogie (every axle has two shaft necks)

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Table 2. The results of the experiments for the same bogie after application of the measures designed to make the necessary corrections for the pressure distribution

Bogie no.	Shaft neck	Pick-up	F_A [daN]	F_B [daN]	F_C [daN]	F_T [daN]	x_F [mm]	y_F [mm]
0081/1980	1	I	576	573	599	1748	12,22	-1,58
		E	382	924	455	1761	-7,47	-4,97
	2	I	534	677	576	1787	7,12	-2,82
		E	456	871	473	1800	-3,39	-1,13
	3	I	542	755	590	1887	4,99	-3,05
		E	376	1029	445	1850	-10,62	-4,47
	4	I	468	730	404	1602	-0,57	4,79
		E	372	890	416	1678	-8,04	-3,15

4. DISCUSSION

Analysing the results presented in Table 1 it can be noticed that the distribution of force F_T is uneven; the point where the overall force applies being displaced considerably.

Following the corrections applied, coordinate y_F was brought to values below 5.7 mm. The values higher than 2,3 mm of coordinate x_F were considered to have a very small influence on the uneven wear of the friction pad.

5. CONCLUSION

A great variation in the distribution of the pressure force of the unevenly worn friction pads has been found. This fact comes as a consequence of the geometrical and kinematical deviation of all of the brake component elements. It has also been found out that there is a close dependence between the values of pressure forces F_A, F_B, F_C on the surface of the pad and the values of the wear.

The lack of parallelism between the surface of the friction pads and the brake disks leads to uneven wear oriented along the friction force. The favourable results found at bogies after a period of service during which correction measures for the pressure force have been applied, prove the usefulness and efficiency of the experimental measures carried out via the force cell devised by the author of the paper.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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