Experimental study of metrological properties of magnetostrictive sensors when changing their design parameters

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Abstract. This paper outlines the study of the causes of the relative error Δ in braking-force metering \(F_T\) using the noncontact magnetostrictive method. The study has been carried out on the roller brake testers used for monitoring a technical state of a vehicle brake system. The authors suggest that the metering error Δ depends on the gap \(\delta_C\) formed between the measuring and magnetizing coils of the sensor and the surface of the shaft on which the magnetostrictive sensor is mounted. Based on this assumption the experimental study is conducted to reveal the dependence of the relative error Δ of the gap \(\delta_C\) that produce a shaft beat \(\delta_{\text{max}}\) inside the sensor. The results of the study indicate that when the shaft \(\delta_{\text{max}} = 0.2\) mm, the metering error of brake force is \(\Delta = 1.4\%\). The given value of the relative error Δ of the braking-force metering does not exceed the maximum permissible value \(\Delta = \pm 3\%\). When the shaft beat \(\delta_{\text{max}}\) increases inside the sensor, the relative error Δ also increases.

1. Introduction

In order to ensure safety under the operating conditions of modern vehicles, it is necessary to monitor a technical state of the vehicle brake system. Monitoring has been performed using road and bench methods. However, the bench methods are more distributed than the road ones due to the fact that the results of control of brake systems are significantly influenced by climatic and weather impact [1, 2].

The main advantage of such methods is that the car systems function in the same way as it is under road conditions, but the car does not move. This factor increases the information content and efficiency of the vehicle brake monitoring system.

Most modern brake testers have a standard construction – they are symmetrical and consist of two identical mechanical blocks, each of which rotates its wheel of the vehicle testing axle. In the design of modern power testers there are separate blocks containing two support rollers which the individual balancing gear motor rotates. The stators of balanced gear motors bear strain sensors of braking-force metering. The design symmetry of the mechanical units of modern brake testers provides equal test conditions for the right and left braking wheels of the vehicle testing axle [2].

The disadvantage of strain sensors used in most brake testers is the presence of friction forces in the drive components, which increase their metering error. This fact is confirmed by the experimental studies that were conducted at the Department of ‘Road transport’ of Irkutsk national research technical university [3, 4].
The noncontact method of braking-force metering with the application of magnetostrictive sensors can solve the problem [5].

The purpose of the investigation is to study the factors affecting the measurement process of the power parameters on the brake roller testers with magnetostrictive sensors.

2. Materials and Methods

The scheme of the tester that implements this method is shown in Figure 1. The tester is a roller set with two sections, each of which has a driven roller 2 and a driving roller 5, as well as a roller of the follow-up control 3 with a sensor measuring the speed of rotation of the wheels.

The device is brought into action by an electromotor 6 with a power of 7.5 kW, which transmits driving torque to the shafts of the drive support rollers 5 using a worm gear 7. The worm gear has a gear ratio at which the supporting rollers rotate at a speed of about 4 km/h [5, 6].

The driving support rollers are connected by a chain drive 4 with driven support rollers 2. The electromotor is run by means of an electromagnetic starter which is switched on by the computer [6].

At the same time, the drive of the support rollers is carried out from a single powertrain which contributes to the simultaneous synchronous switching on and off of the tester drive, as well as the synchronous rotation of both wheels of the diagnosed vehicle.

On the shafts which are connected rigidly to the driven rollers 5, two non-contact magnetostrictive sensors \(S_{Rc}\) are mounted for braking-force metering that transmit signal \(R_s\) similarly to the above-mentioned sensors to the computer monitor 1 [5, 6].

![Figure 1](image)

**Figure 1.** The scheme of the tester that implements a non-contact method of braking-force metering:

1 – driven support roller; 2 – driving support roller; 3 – roller of the follow-up control; 4 – electromotor; 5 – worm gear; 6 – chain drive; 7 – computer.

The magnetostrictive system of braking-force metering \(F_T\) consists of magnetostrictive sensors mounted on the shafts of driving support rollers, an amplifier circuit and signal converters.

Magnetostrictive sensor shown in Figure 2 is a cylindrical metal case 1, inside of which a shaft 4 rotates transmitting the drive torque \(M_t\). In the center of the inner surface of the case there are two magnetizing coils 2. Next to them, on the right and left there are eight coils 3 and 5 measuring the voltage.
of the metal of the shaft 4, acting along the main axles O₁ – O₁ and O₂ – O₂. All coils both magnetizing 2 and measuring 3 and 5 are mounted on soft steel cores. The cores of the coils are fixed rigidly on the body 1 of the sensor so that are equally distant from the rotating shaft 4 on the gaps width  \( \delta_c = 0.4 \) mm. These gaps provide a non-contact interaction between the cores of the sensor with the rotating shaft 4 by means of magnetic fields which are created by the magnetizing coils 2 [7].

Figure 2. Magnetostrictive sensor: 1 – metal body of the sensor; 2 – magnetizing coil of the sensor; 3 – coils measuring the voltage of the metal shaft along the axle O₁-O₁; 4 – rotating shaft; 5 – coils measuring the voltage of the metal shaft along the axle O₂-O₂; 6 – mounting bearers; \( \delta_c \) – the gap between the surface of the shaft and the coil cores.

The use of such measurement systems does not exclude the errors. To improve the efficiency of brake testers used to monitor vehicle brake system on roller testers with magnetostrictive sensors, it is necessary to study the factors affecting the measurement process.

The hypothesis is that the metering error depends on the gap \( \delta_c \) that is between the surface of the shaft 4, on which the sensor is mounted and the measuring 3, 5 along with magnetizing 2 coils of the sensor, which depends on the gap \( \delta_{\text{max}} \) when the shaft is seated in the mounting bearers 6. The gap \( \delta_{\text{max}} \) at the sensor seating points can occur due to wear and tear of the mounting bearers resulting in rotation of the shaft relative to the sensor cores with the shaft beat \( \delta \). The shaft beat \( \delta \) may also occur during operation because of the deformation of the shaft (overload, incorrect installation, etc.) Hence, the experimental study has been conducted to reveal the dependence of the electrical signal of the system for braking-force metering \( U_F \) on the value of the shaft beat \( \delta \).

3. Experimental Section
A designed and manufactured magnetostrictive sensor was used in the experiment [8]. The sensor source voltage \( U_D \) is stabilized with a frequency \( \nu = 50 \) Hz, the maximum amplitude is \( U_D = 36 \) V.

Two shafts were used for the experimental study:
1. standard;
2. simulation.

The standard shaft (Figure 3) is manufactured with permissible variations \( s_6 \) and with no gap in the mounting bearers when installed in the sensor. The simulation shaft is used to determine the calibration constants \( a \) and \( b \), as well as to calculate the relative error \( \Delta \) in braking-force metering \( F_T \). The simulation shaft with reduced bore diameters for the mounting bearers has been applied to simulate the gaps \( \delta_{\text{max}} \).
Figure 3. Pattern of standard shaft: A and B show the surface of the shaft in contact with the mounting bearers.

A measurement scale was marked on the magnetostrictive sensor cover (Figure 4) to determine the angle of rotation of the shaft $\alpha_B$. The sidewall of the shaft was marked with zero marker in the form of an arrow to locate the shaft. By means of set of feeler gauges, the required values of the shaft beat were simulated. It was decided to investigate a simple radial runout in which the gap $\delta_{\text{max}}$ between the surfaces of the shaft A and B (Figure 3, a) and the inner rings of the mounting bearers are equal as it is the most common type of gap $\delta_{\text{max}}$.

Figure 4. The pattern of the sensor which is marked with the scale of measurement on its side cover of the angle of rotation of the shaft $\alpha_B$.

For each position of the shaft rotation $\alpha_B$ with a step of 10 degrees, the measurement of voltage signal $U_F$ of the system for braking-force metering was carried out. From the results obtained, the dependence of the voltage change $U_F$ of signal of braking-force metering system is formed when changing the angle of rotation of the shaft $\alpha_B$. Using the coefficients $a$ and $b$ obtained earlier in the process of calibrating the sensor for maximum values of changes in voltages $U_F$, the dependence of the value relative error $\Delta$ in braking-force metering $F_T$ on the shaft beat $\delta_{\text{max}}$ has been calculated.

4. Result and discussion

During the experimental study, 10 rotations of the shaft were made at different gaps $\delta_{\text{max}}$ between the surfaces of the shaft A and B (Figure 3, a) and the inner rings of the mounting bearers. The size of the gap $\delta_{\text{max}}$ is:

1. $\delta_{\text{max}} = 0.2$ mm;
2. $\delta_{\text{max}} = 0.4 \, \text{mm}$;
3. $\delta_{\text{max}} = 0.8 \, \text{mm}$;
4. $\delta_{\text{max}} = 1 \, \text{mm}$.

The dependence of the voltage change $U_F$ of signal of the braking-force metering system on the angle of rotation of the shaft $\alpha_B$ is shown in Figure 5.

![Figure 5](image1.png)

**Figure 5.** The dependence of the voltage change $U_F$ of signal of the braking-force metering system on the angle of shaft rotation $\alpha_B$: 1 – dependence $U_F = f(\alpha_B)$, at $\delta_{\text{max}} = 0.2 \, \text{mm}$; 2 – dependence $U_F = f(\alpha_B)$, at $\delta_{\text{max}} = 0.4 \, \text{mm}$; 3 – dependence $U_F = f(\alpha_B)$, at $\delta_{\text{max}} = 0.8 \, \text{mm}$; 4 – dependence $U_F = f(\alpha_B)$, at $\delta_{\text{max}} = 1 \, \text{mm}$.

The dependence of the maximum voltage change $U_F$ of signal of the braking-force metering system on the gap $\delta_{\text{max}}$ is shown in Figure 6.

![Figure 6](image2.png)

**Figure 6.** The dependence of the maximum voltage $U_F$ of signal of the braking-force metering system on the value of the gap $\delta_{\text{max}}$.

$U_F = 0.374 \, \delta_{\text{max}} + 0.2101$
The calibration constants $a$ and $b$ were obtained by the use of the standard shaft. These constants were used to convert the voltage $U_F$ of signal of the braking-force metering system to the brake force $F_T$ according to the formula:

$$F_T = a \cdot U_F + b \quad (1)$$

where $a$ is the calibration constant, $a = 11885$; $b$ – the calibration constant, $b = -3110.8$.

Using the obtained values, one can calculate the relative error $\Delta$ of the braking-force metering $F_T$, caused by the shaft beat:

$$\Delta = \frac{F_T - F_{T_{\text{max}}}}{F_{T_{\text{max}}}} \times 100\% \quad (2)$$

where $F_{T_{\text{max}}}$ is the maximum value of $F_T$ when calibrating the sensor, $F_{T_{\text{max}}} = 11.5$ kN.

The dependence of the change of the relative error $\Delta$ of the braking-force metering $F_T$ on the value of the shaft beat $\delta_{\text{max}}$ is shown in Figure 7.

![Figure 7](image_url)  
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\text{Figure 7. The change dependence of the relative error } \Delta \text{ of the brake force } F_T \text{ on the shaft beat } \delta_{\text{max}}.}

The figure shows that the acceptable value of the relative error $\Delta_{\text{accept}} = 1.4$, in which the relative error $\Delta$ of the braking-force metering does not overstep the limits of $\Delta = \pm 3\%$ [9].

### 5. Conclusions

From the results of the experimental study, the following conclusions are drawn.

1) The presence of gaps $\delta_{\text{max}}$ between the shaft surfaces A and B (Figure 3a) and the inner rings of the mounting bearers of the magnetostrictive sensor leads to the instability of the voltage value of the signal $U_F$ of the braking-force metering system. At the same time, the dependence of the voltage change $U_F$ on the gap $\delta_{\text{max}}$ is linear.

2) The voltage change $U_F$ of the signal of the braking-force metering system can reach $\Delta U_F = 0.57$ V at a gap of $\delta_{\text{max}} = 1.0$ mm. The error of the braking-force metering will increase by $\Delta = 32.2\%$ in relation to the maximum value of the brake force $F_{T_{\text{max}}}$. The shaft beat $\delta_{\text{max}} = 0.8$ mm will cause the voltage change in the measurement system of the magnetostrictive sensor $\Delta U_F = 0.52$ V and an increase in the metering error by $\Delta = 27.23\%$. The value of the shaft beat $\delta_{\text{max}} = 0.4$ mm will lead to the change in the signal voltage $\Delta U_F = 0.36$ V, while the metering error of the braking force will increase by $\Delta = 10.47\%$. The instability of the $U_F$ of the signal voltage within such limits leads to an increase in the relative error $\Delta$ of the braking-force metering $F_T$ to $\Delta = 32.2\%$, which exceeds the maximum permissible relative metering error which is $\Delta = \pm 3\%$ [9].

3) Moreover, when the shaft $\delta_{\text{max}} = 0.2$ mm there is a change in the voltage of the metering system $\Delta U_F = 0.27$ V, as a result, the metering error of the braking force will increase by $\Delta = 1.4\%$. This value
of the relative error $\Delta$ of the braking-force metering does not exceed $\Delta = \pm 3\%$ [9], therefore, the shaft beat $\delta_{\text{max}} = 0.2 \text{ mm}$ belongs to a possible range.

**Reference**

[1] Bojko A V, Fedotov A I, Khalezov V P, Mlynczak M 2015 Analysis of brake testing methods in vehicle safety *Safety and Reliability: Methodology and Applications* (Poland: Wroclaw) pp 933–937

[2] Fedotov A I 2012 Vehicle Diagnostics *Textbook for university students on Operation of transport and technological machines and complexes* (Irkutsk: Publishing House of ISTU) p 476

[3] Fedotov A I, Boyko A V, Potapov A S 2007 Measurement reproducibility of the parameters of the car braking system on the brake tester with roller drums *Proc. Int. Conf. (Irkutsk)* pp 26–32

[4] Fedotov A I and Boyko AV 2007 The results of experimental studies of the car braking process on the modern brake tester STM 3500 *Proc. Int. Conf. dedicated to the 75th anniversary of the birth of I P Terskikh* (Irkutsk: Publishing House of ISTU) pp 146–150

[5] Kuznetsov N Yu, Yan'kov S O, Fedotov A I, Beznosov G A 2017 Tester used to monitor a technical state of vehicle brake system *Proc. Int. Conf. (Irkutsk)* pp 417–426

[6] Fedotov A I, Kuznetsov N Yu, Yan'kov O S and Boiko A V, Russia Patent No 1,671,43 (6 December 2016)

[7] Fedotov A I 2012 *Fundamentals of the Theory of Motor Vehicle Operational Properties* (Irkutsk: Publishing House of ISTU) p 122

[8] Yan'kov O S and Chernyshkov A S 2018 Design development of force-measuring magnetostrictive sensor of brake tester *Proc. Int. Conf. (Russia)* pp 53–59

[9] GOST RF 51709-2001 *Vehicles. Motor vehicles and their trailers. Safety requirements for technical conditions and methods of inspection* (Standartinform, Moscow)