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Experimental Study on Wear Loss of Brake Shoe based on Series Resistance

[1] Rong Chen, [1] Jian Su, [1] Xiugang Wang, [1] Ning Li and [1] Tian Yang

[1] *College of Traffic, Jilin University, Changchun, 130022, China.*
E-mail: chenrong@jlu.edu.cn

Abstract

Aiming at problem of real-time detection on wear loss of brake shoe, one kind of sensor based on series resistance was developed, and the test method was put forward. The test models among wear loss, system resistance and output voltage were established, which relied on theory of least-squares calculations. Sensitivity of the sensor and stability of the signal output were determination. Meanwhile, test for certain vehicle was conducted, and the result was consistent to the theoretical value, maximum error was 4.58%, which proved the accuracy of the test methods and test models and the feasibility of the test method.

***Keywords**: Brake Shoe; Wear Loss; Series Resistance; Real Vehicle Test*

1. Introduction

Braking performance is an important evaluation index for the running safety of car [1-2]. Wear loss of brake shoe will weaken the braking response, effect the braking efficiency and braking stability. More seriously, the friction facing will be exfoliated, which lead to a serious traffic accident.

At present, there are two kinds of detection method for the wear loss of brake shoe. One is that detection sensor sent out warning, when brake shoe sensor was worn to a limit value and the sensor circuit switched On; such as the warning systems put out by Yang Zhenning, Si Guoqing, Schmitt H M, which installed the abrasion indicator into the brake-block. But this kind of method did not meet the demand of reality, as it could not transmit the wear data in real-time. The other one is indirect measurement, such as the way to use auto-adjustable arm of brake slack put out by Ma Xiping, Li Guoping, which detected the wear loss via variability of automatic adjustment cam angle. But this method did not meet the requirements of accuracy due to the accumulated error of transmission mechanism.

In order to realize the real-time detection, this paper put out a test method based on series resistance, and designed the sensor. Test model among output voltage, system resistance and wear loss were built. Also, the transducer sensitivity and signal output stability were tested. Meanwhile, experiment for the wear loss via the sensor was carried out, and the test result was close to the theoretical value. The maximum error was 4.58%, which met the demand of technical protocol, and proved the accuracy of test method and model.

2. Sensor Design

2.1. Sensor Structure

Figure 1 is the structure and installation. Figure 1(a) is the general structure, which includes sensor cap 1, sensor shell 2, locknut 3 and sensor chip 4. Figure 1(b) is the chip, which contains circuit substrate, signal line, chip resistors whose precision were 1%. Figure 1(c) is the installation of sensor.

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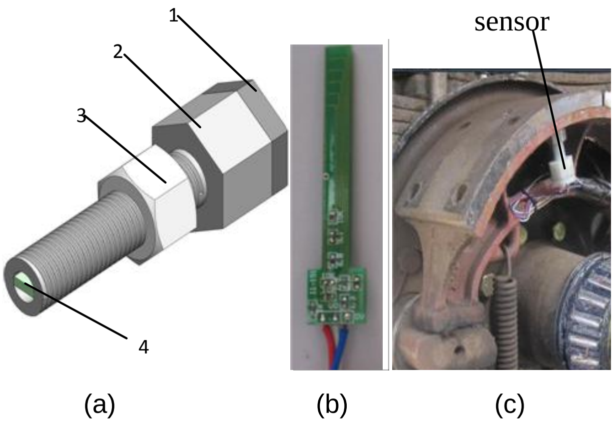

Figure 1. Structure and Installation of Sensor

2.2. Testing Principle

Sensor chip is the key to the measure of wear loss, which transmitted the physical quantity of wear loss to voltage. Figure 2 is schematic diagram of test circuit, it contains12 chip resistors which composed the series-parallel circuit. In figure 2, R_0 was divider resistors, which supplied overload protection; R_1~R_{11} were detecting resistances connected by wire. During the test, as distance ΔS among connecting wires was equality, so, when the wire was broken, value of system resistance changed, value of *Uo* also change. Then the wear loss of the shoe was detected indirectly. Meanwhile, the resistance matching scheme was enumerated in Table 1.

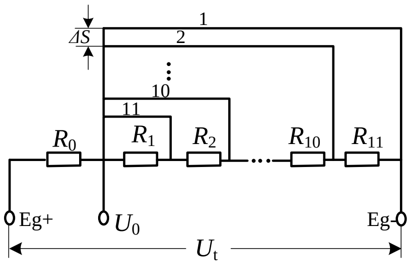

Figure 2. Diagram of Test Principle

Table 1. Matching of Resistance

R	R0	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11
Value/ Ω	1000	510	1500	2050	2550	4020	5490	5490	7150	8250	9090	9090

3. Analysis of Wear Loss Test Model

According to the test method mentioned, relationship among the wear quantity Si(i=0,1⋯11) and system resistance *R*, output voltage *Uo* can be solved as shown in Table 2.

3.1. Model of Wear Loss and System Resistance

Relationship model between wear loss and system resistance was built via least square method [9-12]. The wear loss was expressed as *S*, the system resistance was expressed as *R*. According to the Figure 3, relationship between wear loss and system resistance was nonlinear, oblique way was used liked the formula (1).

$$S(R) = a_0 + a_1 R + a_2 R^2 + a_3 R^3 \quad (1)$$

Table 2. Relationship among Wear Loss, System Resistance and Output Voltage

Wear unit	R/Ω	U_0	S
S_0	10000	0	0
S_1	11510	0.13119 Ut	ΔS
S_2	12510	0.20064 Ut	$2\Delta S$
S_3	13710	0.2706 Ut	$3\Delta S$
S_4	15140	0.339498 Ut	$4\Delta S$
S_5	16920	0.40898 Ut	$5\Delta S$
S_6	19240	0.48025 Ut	$6\Delta S$
S_7	22250	0.55056 Ut	$7\Delta S$
S_8	26370	0.62078 Ut	$8\Delta S$
S_9	32270	0.69011 Ut	$9\Delta S$
S_{10}	41580	0.759499 Ut	$10\Delta S$
S_{11}	51580	0.829112 Ut	$11\Delta S$

According to the least square method, residuals of $|\delta_i|=|S*(R_i)-S_i|$ must be the minimum, which was expressed as formula (2).

$$\sum_{i=1}^{11}(\delta_i)^2=\sum_{i=1}^{11}[S(R_i)-S_i]^2=\min \tag{2}$$

Based on the formula (1) and formula (2), values of a_0、a_1、a_2 and a_3 could be solved as follows.

$$\begin{cases}
\frac{\partial S}{\partial a_0}=\sum_{i=0}^{11}2[S*(R_i)-S_i]=0 \\
\Rightarrow \sum_{i=0}^{11}[S*(R_i)-S_i]=0 \Rightarrow \sum_{i=0}^{11}S*(R_i)=\sum_{i=0}^{11}S_i \\
\frac{\partial S}{\partial a_1}=\sum_{i=0}^{11}2R[S*(R_i)-S_i]=0 \\
\Rightarrow \sum_{i=0}^{11}R[S*(R_i)-S_i]=0 \Rightarrow \sum_{i=0}^{11}RS*(R_i)=\sum_{i=0}^{11}RS_i \\
\frac{\partial S}{\partial a_2}=\sum_{i=0}^{11}2R^2[S*(R_i)-S_i]=0 \\
\Rightarrow \sum_{i=0}^{11}R^2[S*(R_i)-S_i]=0 \Rightarrow \sum_{i=0}^{11}R^2S*(R_i)=\sum_{i=0}^{11}R^2S_i \\
\frac{\partial S}{\partial a_3}=\sum_{i=0}^{11}2R^3[S*(R_i)-S_i]=0 \\
\Rightarrow \sum_{i=0}^{11}R^3[S*(R_i)-S_i]=0 \Rightarrow \sum_{i=0}^{11}R^3S*(R_i)=\sum_{i=0}^{11}R^3S_i
\end{cases} \tag{3}$$

Based on formula (3), equation (4) can be built.

$$\begin{cases}
11a_0+a_1\sum_{i=0}^{11}R+a_2\sum_{i=0}^{11}R^2+a_3\sum_{i=0}^{11}R^3=\sum_{i=0}^{11}S_i \\
a_0R+a_1\sum_{i=0}^{11}R^2+a_2\sum_{i=0}^{11}R^3+a_3\sum_{i=0}^{11}R^4=\sum_{i=0}^{11}RS_i \\
a_0R^2+a_1\sum_{i=0}^{11}R^3+a_2\sum_{i=0}^{11}R^4+a_3\sum_{i=0}^{11}R^5=\sum_{i=0}^{11}R^2S_i \\
a_0R^3+a_1\sum_{i=0}^{11}R^4+a_2\sum_{i=0}^{11}R^5+a_3\sum_{i=0}^{11}R^6=\sum_{i=0}^{11}R^3S_i
\end{cases} \tag{4}$$

According to the Cramer rule, parameters of equation (4) can be set as follows.

$$\Lambda=\begin{vmatrix} 11 & \sum_{i=0}^{11}R & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}R^3 \\ R & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^4 \\ R^2 & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^5 \\ R^3 & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^5 & \sum_{i=0}^{11}R^6 \end{vmatrix}$$

$$A_0=\begin{vmatrix} \sum_{i=0}^{11}S_i & \sum_{i=0}^{11}R & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}R^3 \\ \sum_{i=0}^{11}RS_i & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^4 \\ \sum_{i=0}^{11}R^2S_i & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^5 \\ \sum_{i=0}^{11}R^3S_i & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^5 & \sum_{i=0}^{11}R^6 \end{vmatrix} \quad A_1=\begin{vmatrix} 11 & \sum_{i=0}^{11}S_i & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}R^3 \\ R & \sum_{i=0}^{11}RS_i & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^4 \\ R^2 & \sum_{i=0}^{11}R^2S_i & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^5 \\ R^3 & \sum_{i=0}^{11}R^3S_i & \sum_{i=0}^{11}R^5 & \sum_{i=0}^{11}R^6 \end{vmatrix}$$

$$A_2=\begin{vmatrix} 11 & \sum_{i=0}^{11}R & \sum_{i=0}^{11}S_i & \sum_{i=0}^{11}R^3 \\ R & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}RS_i & \sum_{i=0}^{11}R^4 \\ R^2 & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^2S_i & \sum_{i=0}^{11}R^5 \\ R^3 & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^3S_i & \sum_{i=0}^{11}R^6 \end{vmatrix} \quad A_3=\begin{vmatrix} 11 & \sum_{i=0}^{11}R & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}S_i \\ R & \sum_{i=0}^{11}R^2 & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}RS_i \\ R^2 & \sum_{i=0}^{11}R^3 & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^2S_i \\ R^3 & \sum_{i=0}^{11}R^4 & \sum_{i=0}^{11}R^5 & \sum_{i=0}^{11}R^3S_i \end{vmatrix}$$

Then,

$$a_0={A_0}/{\Lambda}=-11.9,\ a_1={A_1}/{\Lambda}=0.00153,$$
$$a_2={A_2}/{\Lambda}=-3.79\times10^{-8},\ a_3={A_3}/{\Lambda}=3.25\times10^{-13}.$$

Relationship model between wear loss and system resistance was built as formula (5):

$$S=-11.9+0.00153R-3.79\times10^{-8}R^2+3.25\times10^{-13}R^3. \tag{5}$$

The blue curve in figure (3) was the fitted curve of formula (5).

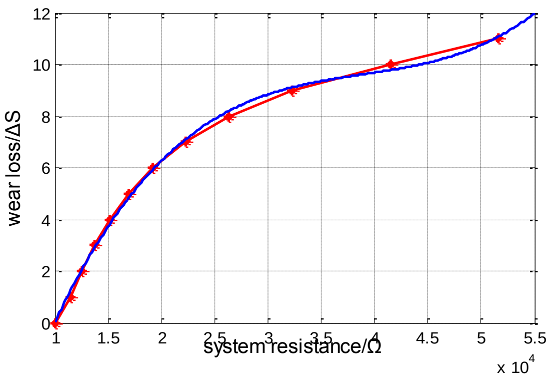

Figure 3. Curve of Wear Loss and System Resistance

3.2. Model of Output Voltage and Resistance

Combine the Figure 4 with data in Table 2, conclusion of the relationship between output voltage U_0 and system resistance R could be obtained, which was nonlinear relation. Relationship model between wear loss and system resistance was built as formula (6) referred to the method of section 2.1.

$$U_0 = -0.894 + 0.000121R - 3.09\times10^{-9}R^2 + 2.71\times10^{-14}R^3 \quad (6)$$

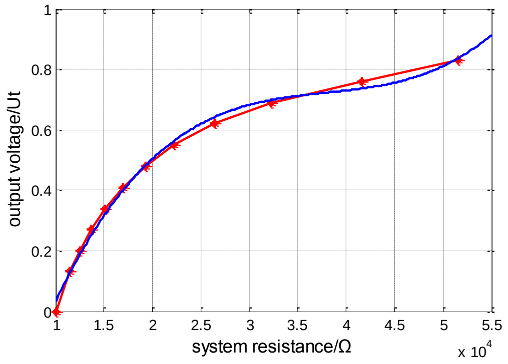

Figure 4. Curve of Output Voltage and System Resistance

3.3. Model of Output Voltage and Wear Loss

Combine the Figure 5 with data in Table 2, relationship between output voltage and wear loss could be obtained, which was linear relation. Also, the model between them could be built like formula (7).

$$S = 13.8U_0 - 0.572 \quad (7)$$

According to the analysis above, relationship between output voltage and wear loss was of good linear relation, meanwhile linearity of the sensor designed was good, which proved the test scheme was feasible.

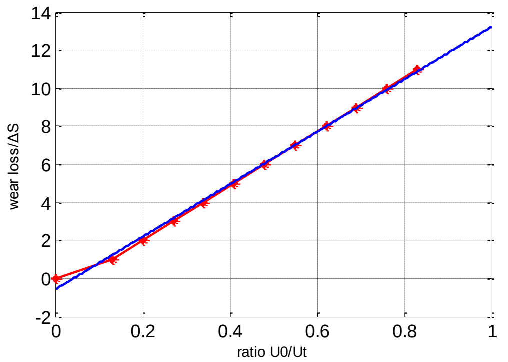

Figure 5. Curve of Wear Loss and Output Voltage

4. Sensor Test

4.1. Sensitivity Test

Sensitivity is the ratio of output and input for the sensor under the steady state condition, which also can be described as the slope of output-input. Variation of output voltage was set as ΔU_0, variation of wear loss was set as ΔS, sensor sensitivity was set as S_n, and then formula (8) was carried out.

$$S_n = \frac{\Delta U_0}{\Delta S} \quad (8)$$

During the test, power supply for the sensor was U_t, which was 5V. Output voltage U_0 could be calculated via formula (9) as follow.

$$U_{0i} = \frac{\sum_{i=1}^{k} R_i}{R_0 + \sum_{i=1}^{k} R_i} Ut \quad (i,k = 1,2 \cdots 11) \tag{9}$$

Table 3 was data of wear loss *S* and output voltage U_{0i} (i=1,2,3···11). Then the relationship model of them can be obtained like formula (10), and the drawing curve also could be get as the Figure 6.

$$U_0 = 0.218S + 0.903 \tag{10}$$

Then the Sensitivity S_n of the sensor was 0.218.

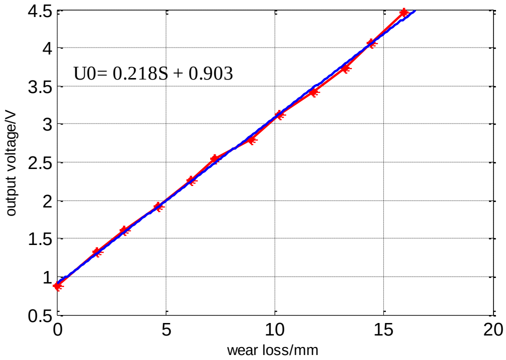

Figure 6. Calibration Curve of Sensor

4.2. Signal Stability Test

Difference between the front and back output voltage was defined as ΔU_{0i} .According to Formula (11) it can be concluded as Formula (12), when the sensor was worn.

$$\Delta U_{0i} = \left(\frac{\sum_{i=1}^{k} R_i}{R_0 + \sum_{i=1}^{k} R_i} - \frac{\sum_{i=1}^{k-1} R_i}{R_0 + \sum_{i=1}^{k-1} R_i} \right) Ut \tag{11}$$

Combined with the analysis of table 3, when the sensor chip wearing, the change of system resistance caused the change of output voltage U_0. The difference between the front and back output voltage U_0 is about 0.3V, which is described as ΔU_{0i}. The variation was uniform and signal output was stability, which met the requirements of the signal test. At the same time, the resistance matching of the sensor was verified as reasonable in the test circuit.

Table 3. Test Result of the Sensor

Definition	U_0	U_{01}	U_{02}	U_{03}	U_{04}	U_{05}	U_{06}	U_{07}	U_{08}	U_{09}	U_{010}	U_{011}
U_{0i}/V	0.873	1.329	1.615	1.918	2.257	2.542	2.802	3.121	3.419	3.728	4.061	4.459
ΔU_{0i} /V	--	0.456	0.286	0.303	0.339	0.285	0.26	0.319	0.298	0.309	0.333	0.398
S/mm	0	1.86	3.11	4.63	6.18	7.23	8.92	10.23	11.77	13.2	14.4	15.92

5. Experimental Verification

Based on the proposed brake shoe wear test method, a real vehicle test has been carried on to track and inspect the wear of wheel brake shoe with the installation of the sensor on the right rear wheel brake shoe. The wearing capacity will be get resulting from the data analysis and processing. Table 4 is the test results.

The theoretical values for shoe worn in Table 4 were the mean values by repeatedly measured and the test values were real vehicle test results by testing model. According to data analysis, the maximum error between system test values and theoretical values was 4.58%. Therefore, the error was small enough to meet the requirements of technical agreement error which was specified as not more than 10%. Experimental results verify the accuracy of the proposed wear test model and implement the shoe wear accurate detection. Hence, the sensor testing design was reasonable.

Table 4. Analysis of vehicle test result

Definition	S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}
Test value/mm	0	1.86	3.11	4.63	6.18	7.23	8.92	10.23	11.77	13.2	14.4	15.92
Theory value /mm	0	1.95	3.26	4.65	6.20	7.50	8.69	10.15	11.52	12.93	14.46	16.28
Absolute error /mm	0	-0.09	-0.15	-0.02	-0.02	-0.27	0.23	0.08	0.25	0.27	-0.06	-0.36
Relative error /%	0	-4.58	-4.56	-0.336	-0.282	-3.627	2.619	0.762	2.199	2.078	-0.385	-2.197

6. Conclusions

(1) Test method of wear loss of brake shoe based on series resistance was put up, and the testing principle was described. Also test models among wear loss, system resistance and output voltage were established, which relied on theory of least-squares calculations.

(2) Sensitivity of the sensor was tested that the value was of 0.218. Also the signal stability test was carried out, and Difference between the front and back output voltage was 0.3V, which conformed to the test requirements.

(3) Test for certain vehicle was conducted, and the result was consistent to the theoretical value, maximum error was 4.58%, which proved the accuracy of the test methods and test modes and the feasibility of the test method.

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Authors

Rong Chen, He received the B.S. and M.S. degrees at Vehicle Operation Engineering in Jilin University of Technology, and Ph.D. degree at Communication and Information System in Jilin University. He is currently a associate professor at College of Traffic in Jilin University. He is a member of the vehicle intelligent detection and diagnosis laboratory in Jilin University. His research focuses on the vehicle intelligent detection and diagnosis.

