Research on Fault Detection Method for Tire Dynamic Balance Measuring System Based on Correlation Analysis

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ABSTRACT

Application of correlation analysis method was studied in fault detection of dynamic balance measuring system. The test data reproducibility in dynamic balance measuring system is a key index of the system's reliability, there are many influencing factors and all of them are with relevance, which make it difficult to troubleshoot the factors that affect the reproducibility of test data in practical project, this has been restricting the development of tire dynamic balance measuring systems. The method of correlation analysis was used to the fault detection for tire dynamic balance measuring system by the first time. The sensitive factors of test data repeatability in dynamic balance measuring system was obtained through the correlation analysis of the measured data in the measuring system, and the measuring system was optimized according to the analysis results, then a series of tests were arranged in the optimized system to verify the correctness of the correlation analysis, thus clarifying the important role of correlation analysis in fault detection.

1. BACKGROUND

Dynamic balance performance is one of the key indexes of measuring the quality of tire and is also an important feature that ensuring safe and smooth operation of tire. But it is difficult for the tire to reach complete uniformity, which is dynamic unbalance, due to raw materials and production process and other reasons. If the unbalance level of tire exceeds the regulated range, it will cause unbalance of tire during operation and even cause accident. Therefore, it must make unbalance test for the tire before delivery, so that the unqualified tire will be picked out. It also proposes higher demand for the accuracy of dynamic balance measuring system, which is that the measuring system not only needs to have the ability of measuring the tire unbalance accurately, but also needs to possess certain stability. These abilities are finally reflected as the accuracy and repeatability of the attained testing data. But in practical project, because dynamic balance measuring system is an interdisciplinary complicated system, there are many influencing factors and all of them are with relevance. It is difficult for traditional method to check out sensitive factors; the designer, installation engineer and debugging engineer have been adopting trial and error method to make systematic improvement, which cost a lot but the improvement effect is not obvious.

In recent years, domestic tire manufacturers and universities have made some researches on tire dynamic balance measuring system. Zhang Jian from Zhejiang University has proposed evaluation method for dynamic uncertainty of dynamic balance measuring system based on Monte Carlo method under Bayesian framework, which promotes static evaluation of system accuracy to dynamic evaluation. Hang Bolin and others have adopted volume calibration, zero mode correction, M*N testing and other methods to test the tire stability. Beijing Aeronautical Technology Research Institute has adopted disengage of spindle system in measuring process and drive motor, removed the interference of transmission belt tension to spindle vibration system and adopted special velocity compensation algorithm. Researches made by foreign countries on dynamic balance measuring system start earlier and are relatively mature. Japanese BANZAI Company has developed CWB series of wheel dynamic balance measuring system. Japanese Bridgestone has developed the biggest automobile tire testing machine MTS to simulate pavement dynamic system in the world in Tokyo. This testing machine has excellent testing performance in velocity, vertical input, lateral force and torque. Sheng Deen of Schenck Process has analyzed the principle error and low mechanical sensitivity issues of hard support balancing machine and pointed out that vibration system design of dynamic balance measuring system in the future should remove principle error and correlation effect of force at maximum and improve swing stiffness, mechanical sensitivity and plane separation.

In this paper, the correlation analysis method is introduced into the fault detection of the tire dynamic balance measuring system, and the correlation analysis is used to find the sensitive factors that affect the repeatability of the test data, then design the test to validate the results.

2. DYNAMIC BALANCE MEASURING SYSTEM

Tire dynamic balance measuring system is special equipment for testing tire dynamic balance, is a complicated equipment of interdisciplinary of machinery, automatic control and computer etc and its structure is as shown in figure 1. Related indexes used to quantify tire unbalance include tire static unbalance, couple unbalance, and unbalance of upper and lower planes etc, which provide basis for adopting compensation measure to remove the dynamic unbalance of tire in the following.

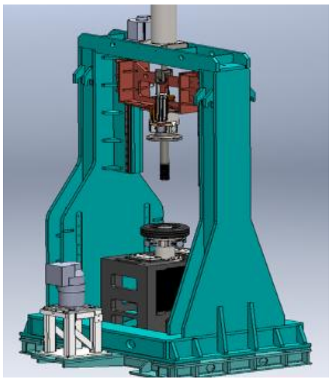

Figure 1 Structure of the system

(1) Static unbalance

Because mass of each part of the tire can’t be absolutely even, it will cause mass eccentricity. If the centrifugal force acting on tire is single, it is static unbalance and the unit is g*cm. Static unbalance mass is static unbalance dividing correction radius and the unit is g. Due to the existence of static unbalance, unbalance will happen to the tire during rotating, which makes the tire bounce up and down and people will feel the vehicle is jumping, its action form is as shown in figure 2.

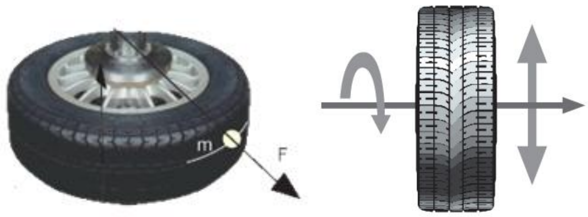

Figure 2 action form of static unbalance

(2) Couple unbalance

Comparing that the centrifugal force of tire centerline is the same and the directions are opposite but it does not act on the same plane, it forms couple, which is couple unbalance. Couple unbalance is couple value and unit is g*m. Unilateral couple unbalance mass is couple unbalance dividing radius of correcting plane and the unit is g. Due to the existence of couple unbalance, the tire will lose balance during rotation, which makes the tire swing to the left and right. The passenger will feel the swing of the vehicle and its action form is as shown in figure 3.

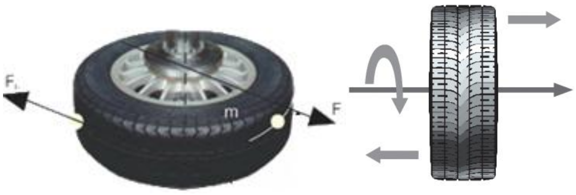

Figure 3 Action form of couple unbalance

(3) Unbalance of upper and lower planes

It is calculated based on parallelogram rule of vector addition. The synthetic quantity of static unbalance mass and couple unbalance mass on the same correction plane can be divided into upper unbalance mass and lower unbalance mass and the unit is g.

(4) Dynamic unbalance

Dynamic unbalance is the combination of static unbalance and couple unbalance. It makes the tire present random vibration during rotation, which is the superposition of above described bump and left and right swing, the action form is as shown in figure 4.

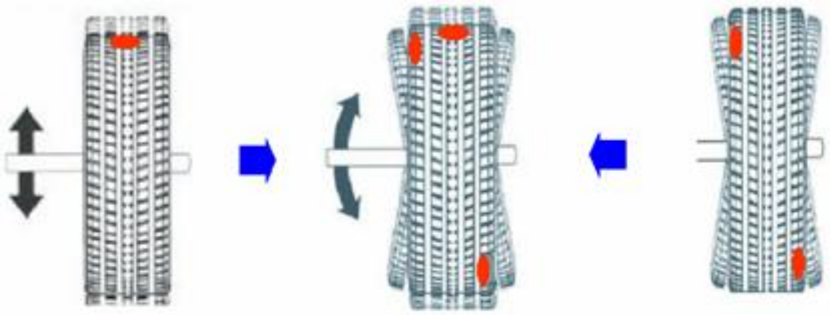

Figure 4 Action form of dynamic unbalance

3 EXPERIMENTAL DESIGN AND ANALYSIS

Tire dynamic balance measuring system structure is more complex, and there is correlation among the influence factors, so there are two major problems in solving the stability of the dynamic balance measuring system: identify the influence factors, and maintain / improve the system. In this paper , at first, found the influence factors of the stability of the dynamic balance measuring system by using FTA, and then make the test planning and put the test into effect, through the analysis of the test data, found a clear direction of system improvement, and then verify the effect of the optimized system, verify the correlation analysis method is effective in dynamic balancing measuring system fault detection , and optimization dynamic balancing measuring system continuous like the cycle process referral before. The process is shown in figure 5.

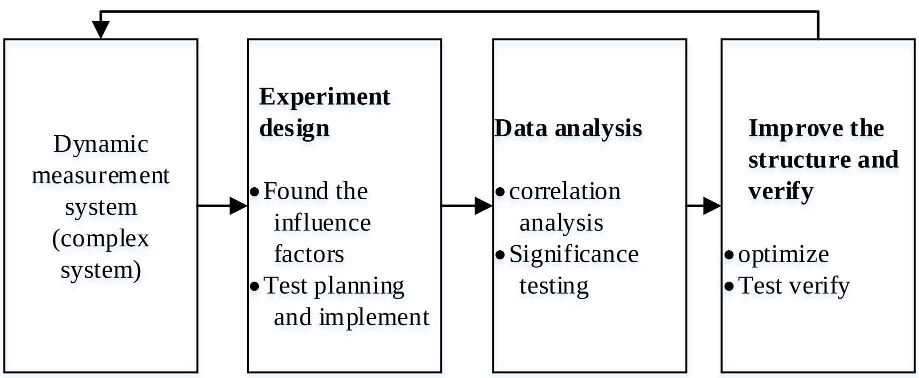

Figure 5 Work process

3.1 Experimental design

The paper based on the dynamic balance measuring system of MESNAC, build a FTA of the system, according with the problem, analysis the root cause for poor repeatability of the measuring system test data, found the influence factors. Because the whole fault tree model is relatively large and the company's confidentiality requirements, this paper made a deletion of the bottom event, only gave main fault tree model, as shown in figure 6.

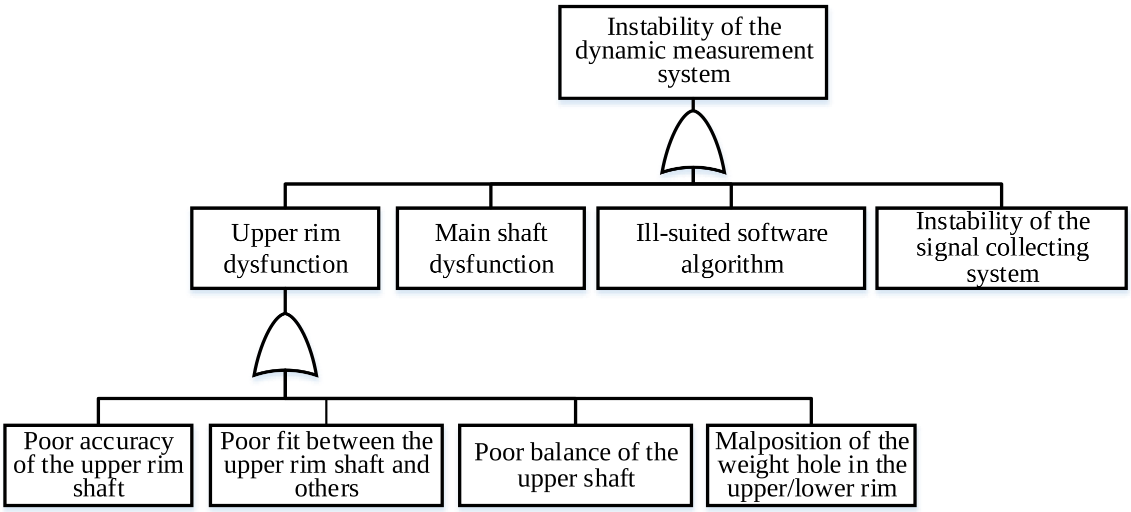

Figure 6 Fault tree

Through the FTA of the dynamic balance measurement system, 122 bottom events was found, and because of some reasons, we just focus on the controllable bottom events. In order to assess the importance of each basic event, organization the experts like designer, QA engineer, debugging, electrical engineer, fitter ,etc., finally proposed the controllable key factors ,as shown in Table 1

Table 1 Key factors list

No	Controllable event		Influence factors	Current status	range
1	Lower shaft influence the repetition of the upper rim shaft	Poor fit between clamp splice and upper rim	Face /Radial runout of upper rim shaft	0.05mm	Variation range in 0.02mm，value 《=0.05mm
		Poor fit between upper rim and main shaft joint			
		Inconformity of the clamp splice action			
2	Upper rim shaft does not reach the designated position		Dislocation angle of the up / down spindle (°)	5°	0-8°
3	rotate demonstration dysfunction		Perpendicularity of the main shaft (mm)(sensor direction and motor direction)	/	/
4			Height difference between main shaft and belt wheel	/	/
5			Levelness of motor fitting surface	/	/
6	Ribbed belt tension		/	Can’t be controlled, just depend on people’s feel	/
7	Poor accuracy of rotary joint		Flange run out	/	/

In order to reflect the true condition of the system by testing, we must simulate the true conditions, and as shown in Table 2According to the test conditions given in Table 2 to adjust the test system, in the same test conditions, calibration and eccentricity compensation the dynamic balancing system which with tire, recording the compensation data. Then continuous unloading and rotary to test the dynamic balancing, recording the face /redial runout of upper rim shaft, dislocation angle of the up /down spindle, ribbed belt tension, perpendicularity of the main shaft and other parameters in the process, the measurement method and test frequency and time are shown in table 3, do the test continuous until the system run full 7 days. After the system is stopped, the above values are recorded once again, and derived the continuous test data, and then the test the eccentricity compensation again, and record the data.

Table2 Test condition

No	Item	Car /light truck tire
1	Rotate speed	500—700（±0.5%）
2	Inflation pressure（Mpa）	0.2（±0.01 ）
3	Environment temperature	5—40℃
4	tire	195/65R15 Weight 11.5Kg

Table3 Test parameter and measurement method

<table>
<tr><th>No</th><th colspan="2">parameter</th><th>method</th><th>instrument</th><th>remark</th></tr>
<tr><td>1</td><td rowspan="3">The run out of upper rim shaft</td><td>Radial runout</td><td rowspan="3">Test the data with dialauge when the tire was load and inflated
The MB-PG was fixed in the test fixture ,and header was fixed in the upper rim</td><td rowspan="3">Dialgauge</td><td rowspan="3">Twice/ day
Test without running</td></tr>
<tr><td>2</td><td>Face runout</td></tr>
<tr><td>3</td><td>Angle of the place with biggest runout</td></tr>
<tr><td>4</td><td colspan="2">dislocation angle of the up / down spindle (°)</td><td>Connect the signal of the encoder and proximity switch with oscilloscope.
Calculate the quantity of A-pulse between edge of proximity and Z-pulse of encoder</td><td>Oscilloscope</td><td>Continuous ,and guarantee with the runout data at the same time</td></tr>
<tr><td>5</td><td colspan="2">Perpendicularity of the main shaft (mm)</td><td>Put the dialgauge on the main shaft, rotary the shaft, record the data</td><td>Dialgauge</td><td>Twice/ day
Test without running</td></tr>
<tr><td>6</td><td colspan="2">Height difference between main shaft and belt wheel</td><td></td><td>Filler gauge</td><td>Test before calibration</td></tr>
<tr><td>7</td><td colspan="2">Levelness of motor fitting surface</td><td></td><td>Gradienter</td><td>Test before calibration</td></tr>
<tr><td>8</td><td colspan="2">Ribbed belt tension</td><td></td><td>Tensiometer</td><td>Twice/ day
Test without running</td></tr>
<tr><td>9</td><td rowspan="2">The runout of flange of rotary joint</td><td>Radial runout</td><td rowspan="2">The MB-PG was fixed in the plate ,and header was fixed in the flange</td><td rowspan="2">Dialgauge</td><td rowspan="2">Twice/ day
Test without running</td></tr>
<tr><td>10</td><td>Face runout</td></tr>
</table>

Note：In actual work, the system need to calibration every 5 days, and the system can ensure that the deviation of the test data will be less than 5g.during the 5 days. For the whole process of the system's state, the system should keep running for 7 days, and overall considerate the amount of data and collection workload, set down twice per day for collection.

3.2 Data analysis

3.2.1 Principle

(1) The principle of correlation analysis

The correlation analysis is an statistical method to study whether there is a relation between the factors, and to explore the direction and degree of the related factors. Linear correlation analysis is a common method of correlation analysis, which describes the degree and direction of linear relationship between variables by correlation coefficient R.

If there is a functional relationship between the variables Y and X, then r=1 or -1; if there is no relationship between the variables Y and X, r=0; if the relationship between Y and X is statistical, -1<r<1. Where r>0 is positive correlation, r<0 is negative correlation. Generally speaking, there was a significant correlation when |r|>0.95, |r|>0.8 is

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{x})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 (y_i - \bar{x})^2}} \quad (1)$$

In the formula (1), $\bar{x}$、$\bar{y}$ are the mean of variables x、y; x_i、y_i are the No. i values of variables x、y.

(2) Significance test of correlation analysis

In order to determine the significant degree of the key factors and the output characteristics of the dynamic balance measuring system, it is necessary to test the significance of the correlation coefficient. Here we put the significance level of 5%, which means that the input and output are correlated with the confidence level of 95%, that is to say, the input factor is the sensitive factor to the system.

highly correlation, 0.5<|r|<0.8 has moderate correlation, 0.3<|r|<0.5 has lowly correlation, |r|<0.3 is very weak, that is not related.

Method to calculation the correlation coefficient which commonly used: Pearson, Spearman and Kendall。

The Pearson correlation coefficient is mainly used to calculate the data of fixed distance variables, formula is shown as formula (1).

General inspection procedures are as follows:

A. Put forward the hypothesis: H0: ρ=0，H1: ρ≠0；

B. Computational test statistic:

$$T = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \sim t(n-2)$$

Determine the significance level α, determine the significance: if |T|>tα/2, reject H0; if |T|<tα/2, accept H0.

3.2.2 Test data and analysis

(1) Test data

The experimental data presented in this paper is the sample data, as shown in Figure 7. In the detection of the same tire unbalance, the variation of data measured by the system was bigger than 5g (the allowed range), which was shown in the figure 7.

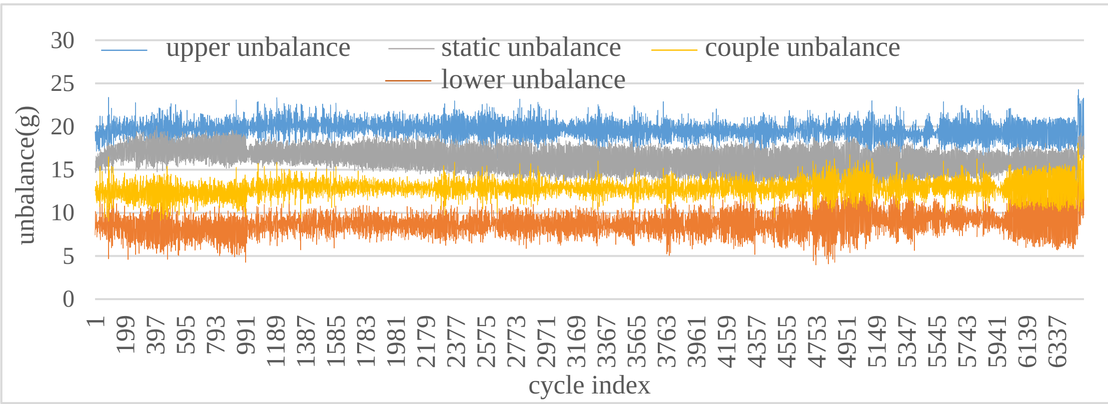

Figure 7 Test data

(2) data analysis

According to the test data of the system, all factors were analyzed based on the correlation analysis method, and the value of significance was not higher than 0.05 were shown in table 4.

Table4 Result

Unbalance	Parameter	Significance	R	Degree of correlation
Upper unbalance	Face runout of upper rim shaft	0.046	0.441	Lowly correlation
	dislocation angle of the up / down spindle	0.0303	0.473	Lowly correlation
	Ribbed belt tension	0.000009	0.810	High-positive correlation
Lower unbalance	Face runout of upper rim shaft	0.040	0.452	Lowly correlation
Static unbalance	Face runout of upper rim shaft	0.024	-0.491	Lowly negative correlation
	Radial runout of upper rim shaft	0.0074	-0.566	Moderate negative correlation
	dislocation angle of the up / down spindle	0.035	0.463	Lowly correlation
Couple unbalance	Face runout of upper rim shaft	0.007	0.570	Moderate correlation
	Ribbed belt tension	0.0134	0.53	Moderate correlation

From the table, for the dynamic balance measuring system, there are significant lowly/ moderate correlation between the upper rim shaft's runout and all kind of unbalances, there is lowly correlation between static unbalance /static unbalance and dislocation angle of the up / down spindle, and high-position or moderate correlation between upper unbalance /couple unbalance and ribbed belt tension. There is a moderate negative correlation between the radial runout of the upper rim shaft and static unbalance.

3.3 improvement and validation

Through the data analysis, the sensitive factors of balance measuring system are face/ radial runout of upper rim shaft , dislocation angle of the up / down spindle and ribbed belt tension .Optimize the measuring system according to the controllable events corresponding to the sensitive factors given in Table 1, ① modified the processing of clamp splice ,to improve the precision of the clamp splice, ②increase the wear resistance of the upper rim shaft by heat treatment, ③install the ribbed belt according to the install norm, tensioning the belt strictly based on the value which calculated by the designer ,④change the servo motor pulse amount which corresponding the place of main shaft rotary 360°, optimize the structure of proximity switch inductor ,to guarantee that the upper rim can stop at the real place. The improved system is tested according to the method described in this paper3.1, and the data are shown in Figure 8.During the whole process, the deviation of data was less than 5g except the static unbalance.

Figure 8 Test data for improved system

4 CONCLUSION

In this paper, qualitative analysis by FTA and quantitative analysis by correlation analysis were combined to determine the sensitive factors that affect the reproducibility of the test data in tire dynamic balance measuring system, and then guided the designers to optimize and verify the system. The results of the test data showed that the correlation analysis could effectively identify the sensitive factors that affect the reproducibility of the test data in the tire dynamic balance measuring system, and though optimized the controllable events corresponding to the sensitive factors, the impact of some sensitive factors on the reproducibility of test data were eliminated, and the reproducibility of test data were significantly improved. Therefore, it is of practical engineering significance to introduce the correlation analysis method into the fault detection for tire dynamic balance measuring system.

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