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RESEARCH ON THE APPLICATION OF PIEZOELECTRIC FORCE SENSOR BASED ON TIRE DYNAMIC BALANCE DETECTION TECHNOLOGY

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ABSTRACT

The sensor is an important component in obtaining signal of the tire dynamic balance detection system. It is an apparatus converted the vibration signal generated by the imbalance into electric signal without distortion. Therefore, the number and mounting position of the sensors, the mounting and preloading methods are key elements should be researched. During this tire balancing detection system, according to the frequency range of the signal, piezoelectric force sensor of KISTLER is adopted. Detailed steps of the sensor mounting and preloading are put forward. Based on the abnormality signals come from engineering practice, it analysis the key problems that may occur in the process of installation and preload. It discusses the influence of sensor nonlinearity on the measurement accuracy. Furthermore, the best calibration test weight value of different models of tire balancing test machine is determined by experiment. Sensors' Correlation effects on the accuracy of plane separation are also researched. It provides a theoretical basis for the mechanical structure design. It laid a foundation for the tire balancing machine design, which is with a high plane separation accuracy.

Keywords: *Piezoelectric Force Sensor, Tire Dynamic Balance Detection, Sensor Nonlinearity, Sensor Correlation Effects*

1. INTRODUCTION

The tire dynamic balance detection is to simulate the actual operating conditions, to identify the value and location of the unbalance amount of the tire itself. And then adding or reducing the unbalance of tire at the corresponding position. Thereby, to reduce the vibration and abrasion of the vehicle components caused by unbalanced centrifugal force. Tire balancing detection system mostly includes signal acquisition, signal conditioning (filtering and amplification etc.) and signal analysis process (extracted the amplitude and phase after A / D converter, and equivalent and conversion of the voltage value to the unbalance amount) [1]. The hardware composition of the control system is shown in Figure.1. Acquiring high-quality vibration signal is the most important step to ensure the high-precision of the dynamic balancing measurement. Therefore, the choice, installation and use of the sensor play an important part in vibration measurement system.

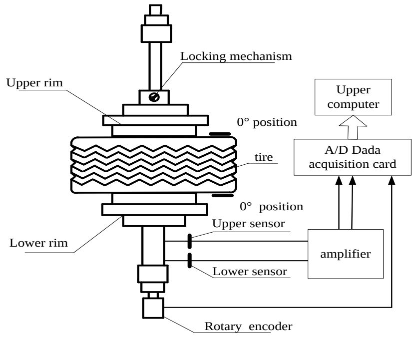


Figure 1 : Composition of The Control System

As piezoelectric quartz sensor with high stiffness, good linearity, hysteresis-free, high natural frequency, especially its high insulation resistance and outstanding stability [2], hence, it is widely used in scientific research, automatic detection and control system. At present, piezoelectric acceleration sensor are widely used as sensitive device to measure the vibrations caused by unbalanced mass both at home and abroad. Since this type of sensors is to measure the vibration of the acceleration value, so when under the same displacement amplitude, the acceleration value is proportional to the square of the signal frequency. Therefore, for a low frequency band signal, the acceleration value may be quite small, while for the high-band signal, the acceleration value may be very large. This is to say that the acceleration sensor is not suitable for measuring the high and low ends frequency vibration signal [3]. As balancing speed of this measuring system is 420r/min, corresponding to the signal frequency is7Hz, which is a low frequency signal, so it considers using piezoelectric force sensor of KISTLER to measure the vibration signal of cyclical centrifugal force transferred by the vibration system. Such a sensor is with a simple structure, a wide measurement range, high sensitivity, good frequency characteristics, especially its high stiffness and resonant frequency, to ensure the transmission of the vibration force without loss. It is particularly suitable for dynamic measurements. However, there are also some disadvantages such as the linear range is narrow, the output impedance is high, the output voltage is relatively weak. So a amplifier is always needed. In light of this, some researchers use control theory principles to analyze and compare the impact of the piezoelectric voltage amplification system and the piezoelectric charge amplifier system on the dynamic characteristics of the quartz force sensor. The results show that: the sensitivity of the piezoelectric voltage amplification system not only depends on the equivalent capacitance of the quartz, but also effects by the capacitance of connecting wire. And the system can not measure the slow-changing signals, too. Meanwhile, since the role of the charge amplifier, the amplification system of the piezoelectric charge sensitivity only depends on the capacitance of the charge amplifier, a DC signal and a relatively slow varying signal can be also reproduced [4]. Therefore, the piezoelectric quartz sensor application should be connected to the charge amplifier.

This article focuses on the installation of the sensor (number, location and method), the influence of sensor nonlinear on the measurement accuracy, the sensor correlation effects on the plane separation accuracy, and experiments have put forward.

2. SENSOR INSTALLATION

2.1. The Number and Installation Location of Sensors

The tire dynamic balancing detection includes the magnitude and angle of static unbalance and even unbalance. Therefore, it uses double-sided balance and influence coefficient method to solve the imbalance. The precision of the influence coefficient effects by three factors: the number and position of the balancing planes; the balancing speed and critical speed; the number and location of the measurement point. The last one factor is mainly refers to the number and mounting position of sensors. The number of sensors, the axial installed position and circumferential position of the sensor, these three points constitute the basic elements of the sensor, which must carefully analyze during the solving process of the dynamic balance, and also the indispensable factors have to be supplied in the final dynamic balancing technology report.

If the number of balance speed is N, the number of measurement points (number of sensors) is M, the number of balance plane is K. When NXM <K, the equation is over determined, it should give up some correction plane. When NXM = K, the equation has a unique solution, i.e. a group of correction quality can be obtained. While when NXM> K, it is a contradictory equation, so the method of least square can be used to obtain a set of corrected mass. Under the national standards and industry regulations and habits, tire balancing test usually at a certain constant speed, and in the method of two balance plane correction, so the number of sensors should be at least 2. Due to a plurality of different sensors at the same measurement section do not provide more independent information for distinguishing rotor’s vibration characteristics at the axial direction. Therefore, the sensors are respectively mounted on the two different measurement sections in order to maximize each role of the sensor. Figure.2 has shown part of the actual equipment, the three holes on the square case are the positions of sensor mounting. Usually, the more the number of axial distribution of the measured section, the more detailed vibration information could be acquired. However, it is not possible to indefinitely increase the number of measured section in the actual practical applications. And for this detection system, especially in the case of test speed is much lower than its first order critical speed, the vibration data obtained by the two measuring section has been well reflect its vibration morphology. The measurement section distributed along the axial should stay away from the modal node. If the measurement section is too close to a modal node of a certain vibration type, the sensor of this section is not sensitive enough to the modal response, so that the measurement data corresponding to the modal will become too small. Under this situation, the data prone to interference by noise. What worse is that it could lead to a morbid influence coefficient matrix, and make the final balance results lack of feasibility [5]. Based on finite element modal analysis, two pairs of sensors have installed both at the up and down bearing support, and the sensor down coupled by two sensors.

Figure 2 : Actual Mounting Locations Of The Sensors

2.2. Sensor Mounting and Preloading [6]

The force to be measured is transferred via the cover and the base of the seal-welded steel case to the quartz sensor elements. When subjected to a mechanical load, quartz produces an electrical charge proportional to that load. The sensor sensitivity (a material constant of quartz) and thus the response threshold is practically the same in all load washers. This offers three unique advantages: (1) even very small force can be measured with a sensor with s wide measuring rang giving substantial overload safety. (2) A sensor with a wide measuring range can be selected in cases where highest possible rigidity is required. (3) Several sensors can be connected electrically in parallel to a single charge amplifier. The output voltage is then proportional to the sum of all active forces.

Load washers should basically be used only preloaded in a mounting structure, either directly in the force flux of a separate component or in force shunt mode embedded in a machine structure. With direct force measurement, almost the entire process force flows through the sensor. The measuring range must therefore be selected so that the sum of preloading force Fv and maximum occurring process force Fz is within the measuring range of the sensor. And the mounting surfaces must be flat, rigid and ground. Sensors are delivered uncalibrated, because in any case they must be calibrated in situ in the mounting structure for absolute measurements. A mounting set consists of a high-tensile stainless steel preloading bolt, a centering sleeve and two insulating washers. The preloading bolt produces a force shunt of 7-9% and a correspondingly reduced sensitivity. In general, a preloading force of at least 20% of the measuring rang is recommended; with tensile forces this should be increased accordingly. If possible (considering the process force), preloading of 50% of the measuring range should be used, because the tolerance with regard to bending moment is then at its greatest, see as Figure.3. However, in the case of force shunt measurements it is loaded with only a very small part of the process force.

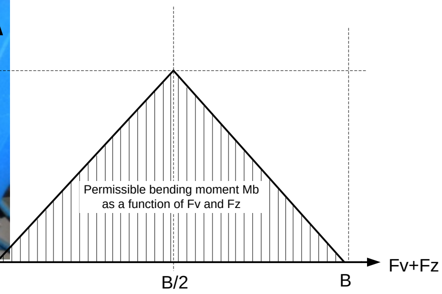


Figure 3 : Bending Moment Of The Sensor

For this type of sensor, load washer for force measurement in the Z direction. Bending moments may not only have a negative influence on the measurement, but may even lead to destruction of the sensor. The permissible value for the bending moment Mb is dependent on the sum of the preloading force Fv and the current process force Fz applied, in which the maximum possible bending moment Mb,max is reached at Fv+Fz= B/2. With the specific values of and Mb,max, the permissible pure bending moment as a function of the preloading force Fv and the process force Fz can be estimated as follows:

$$Mb, perm. \le \frac{2.Mb,\max}{B}.(Fv+Fz);\;\; Fv+Fz \le B/2 \quad (1)$$

$$Mb, perm. \le \frac{2.Mb,\max}{B}.(B-Fv-Fz);\; Fv+Fz \ge B/2 \quad (2)$$

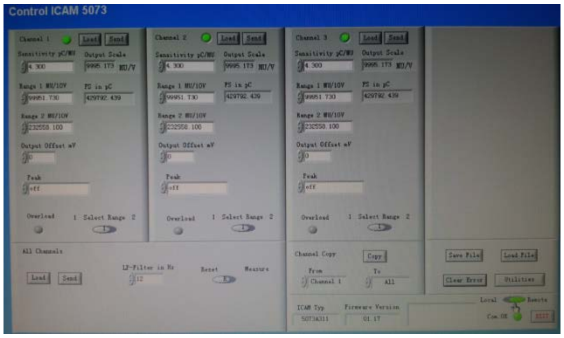
The range limit value B and maximum possible bending moment Mb,max could obtain from the specific table of the certain type sensor supplied by the KISTLER company. According the up two equations, the minimum preloading force required or the maximum permissible preload force can be calculated as a function of other parameters.

In preloading, the force must be measured with the sensor itself, using the sensitivity stated in the Technical Data 4.3pC/N. Since the preloading screw produces a force shunt, the sensor must be calibrated again after mounting in order to determine the sensitivity of the particular measuring direction.

For this tire dynamic balance detection system, 100000 machine units is corresponds to 10V. The preloading parameters and interface is showed as Figure.4. The range is to be set so large enough that avoid overload during the whole preloading process. Once the preloading process finished, the range should be changed to 5000 machine units (for the truck tire). Because if the range is too large, the amplitude of the signal obtained is too small. Under this situation, it difficult to distinguish the useful signal from the other noise signal. This behavior will reduce the sensitivity of the sensor. In other word, the range could be improved and altered according to the actual value of the signal. Furthermore, a data acquire interface of the preloading process has been designed. During the whole preloading process, the change of the force is able to be monitor easily and vividly.

3. SENSOR INSTALLATION

Since the preloading screw produces a force shunt, the sensor must be calibrated again after mounting in order to determine the sensitivity of the particular measuring direction. Meanwhile, the relationship between the input and output need to be quantified, the system should be calibrated to obtaining the transfer function of the system. Hence, a known weight has added on the correction surface to get the calibration coefficients. After calibration, it needs to solve the amount of eccentricity of the system itself. In order to get the unbalance of the tire itself, for each normal test, it must subtract the eccentric of the system. Finally, apply the results of the zero correction to verify the accuracy of the calculations. Zero correction is a regression test method operated after the system calibration and eccentricity compensation. Only the results of zero correction consistent with the test weights loaded on the rim, the conclusion is reasonable and effective.



Channel 1 / Channel 2 / Channel 3:
Sensitivity pC/MU 4.300
Output Scale 9995.173 MU/V
Range 1 MU/10V 99951.730
FS in pC 429792.439
Range 2 MU/10V 232558.100
Output Offset mV 0
Peak off

LP-Filter in Hz 12
Channel Copy From Channel 1 To All
ICAM Typ 5073A311
Firmware Version 01.17

Figure 4 : The Preloading Parameters And Interface

Because the mass of calibration weight is m, so the calibration parameters can only be a good description of linear relationship about the imbalance is m or near. When there is a large deviation between the unbalance of tires and the added weight m, it may not use the obtained parameters to describe the linear relationship of system. To this end, to put weights with different mass on the same position of the rim, to observe the relationship between the sensor signal and weight loaded, the experiment results shown in Figure. 5.

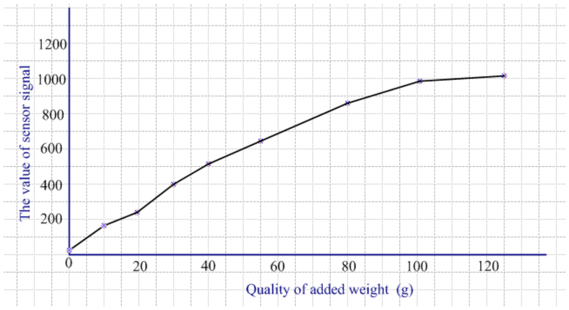


Figure 5 : Relationship Between The Sensor Signal And Weight Loaded

As can be seen from the Figure.5, the relationship between sensor signals and test weight blocks is not strictly linear. Piecewise linear description seems more accurate. So if we use calibration parameters obtained with a test weight 50g to calculate the unbalance of the tire of 100g or 10g, the measurement results may appear a large deviation. The greater deviation between the unbalance of the tire and the test weight, the results obtained may appear larger error. Once the non-linearity of the system is increased, the measurement results may come with a large error. Therefore, during the process of system design and calibration, non-linear factors of the system should be toke into account to reduce the error to minimum. It is better to choose the weight within the linear measurement range of the sensor.

Some researchers have been proposed to use the composition of the weights of different mass calibration method, namely according to the approximate distribution range of the amount of unbalance, select and combine different weights which are within the range to do calibration [7]. The parameters obtained in this way may be more suitable for a broader range of unbalance measurement system. But the imbalance of a tire is unknown, its value is also unable to be predicted. During the actual practice, only can be based on the long-term statistics and analysis to choose the right weights for calibration. Even though, this paper presents an experiment to do calibration and zero correction with different quality of weight value, measurement error statistical results are shown in Table 1. Table 2 have shown the calibration and zero correction results of semi-steel tire dynamic balance detection system with 50g weight, Table.3. has contained the calibration and zero correction results of steel tire dynamic balance detection system with 100g weight.

Table 1: Measurement Error Obtained With Different Weights

Mass of added weight	The average calibration error（%）
10	3.3673
20	2.1452
30	1.53421
40	1.33342
50	1.1098525
100	0.83335
120	2.3569

For the semi-steel tire dynamic balancing test system, added 50g weight at 0 degree position of the upper rim, the amplitude error of the zero correction results on upper balance surface is 0.80599%, while on the lower balance surface is 1.27588%. Added 50g weight at 0 degree position of the lower rim, the amplitude error of the zero correction results on upper balance surface is 1.29012%, and on the lower balance surface is 1.1098525%.

Table 2: Zero correction results of semi-steel tire with 50g weight

		Upper balance surface	Lower balance surface
weight added at 0° position of upper rim	Group 1	A:50.1628	A:0.71402
		α:0.9444	α:212.916
	Group 2	A:49.1818	A:0.6072
		α:357.986	α:48.2929
	Group 3	A:49.33462	A:0.4766
		α:354.7323	α:117.7156
	Group 4	A:50.618	A:0.7736
		α:0.59538	α:15.2109
weight added at 0° position of lower rim	Group 1	A:0.60339	A:49.52162
		α:346.8457	α:1.0963
	Group 2	A:0.85153	A:49.31215
		α:336.8478	α:359.2168
	Group 3	A:0.48251	A:49.5651
		α:331.6032	α:359.4683

Table 3: Zero Correction Results Of Steel Tire With 100g Weight

	Upper balance surface	Lower balance surface
Without test weight	A: 0.3272	A: 0.4283
	α:106.7253	α:207.5637
0° position of upper rim	A: 99.8280	A: 0.22719
	α:359.4057	α:71.9237
90° position of upper rim	A:101.8354	A:1.8198
	α:90.4452	α:345.1295
180° position of upper rim	A: 99.6658	A:1.1956
	α:188.8882	α:35.9471
0° position of lower rim	A: 0.0761	A: 99.8368
	α:157.8446	α:0.4859
90°position of lower rim	A:1.5482	A: 98.3547
	α:173.2583	α:89.8134
180° position of lower rim	A: 0.9652	A: 99.1524
	α:223.364	α:181.3283

For the steel tire dynamic balancing test system, respectively added 0g weight at 0 degree position, 100g weight at 0 degree position, 100g weight at 90 degree position and 100g weight at 180 degree position of the upper rim successively. The amplitude error of the zero correction results on the upper balance plane is 0.6672%; on the lower balance plane is 0.9177%. Also added weights on these positions n the lower rim respectively, we can get the amplitude error of the zero correction results on the upper balance plane is 0.8854%; on the lower balance plane is 0.83335%.

In view of the above experiment, for this developed tire balancing test system equipment, steel tire usually calibrated using 100g weight, and semi-steel tire applying weight of 50g.

4. IN FLUENCE OF SENSOR RELATED EFFECT ON THE ACCURACY

In the ideal measurement system, a physical quantity is usually directly measured by a sensor. In practical applications, when measuring multiple physical quantities, it is necessary to use multiple sensors to work together for each actual value of the physical quantity. So , a physical quantity sometimes must be indirectly obtained by calculated the measured value of two or more sensors, or more physical quantities will at the same time affect the measurement values of a sensor , we define the relationship between the measured physical quantities and the measured values of sensor as correlation effect [8]. For systems that with correlation effects, as long as the changes of the sensor-sensitivity caused by external factors and results error, the final measurement results will be affected and produce deviation because of the effect of correlation.

In tire balancing test system, when balance surface coincides with the measured section, there was no force associated. Then two groups of sensors can be calibrated individually, i.e. on the up balance surface adding weight can calibrated the up sensor, on the lower balance surface adding weight can also calibrate the sensor down individually ,and also can achieve a idea separation of plane and a good separation ratio of static unbalance and couple unbalance. But in fact, it is usually impossible to set sensors in the correction plane, the measuring section and the correction are separated. The association effect of the force is inevitable. Since the sensors are installed in different locations, the dynamic load force at each bearing produce different effects on the performance of each sensor, When the sensitivity change of the two sensors is not the same, because of the force association effect, either adding weight individually on the left correction plane or on the right correction plane, there will be a response in the two measurement channels, that must be calibrated indirectly by solving the equations and may increase the possibility of error. Table. 4 has shown the correlation data when not considering related effect of the sensor. Added 100g weight on the balance surface, the results on both the two balance surface should be close to the original 100g. However, there is a gap between the 100g and the actual data. And the plane separation is also not so satisfactory.

Table 4: Zero Correction Results Of Steel Tire With 100g Weight Without Considering Sensor Related Effect

	Upper balance surface	Lower balance surface
Without test weight	A:0.7742	A:0.365
	α:164.3822	α:354.2164
0° position of upper rim added 100g	A:84.2013	A:22.5245
	α:0.4346	α:309.8809
0° position of lower rim Added 100g	A:28.53	A:77.3937
	α:241.1203	α:357.127

During the preload and calibration process, it should also avoid the phenomenon that preloading one sensor channel, another channel producing response. This association state may lead to a mutual influence between the respective channels of the sensor during the test process, what's more serious is that the sensor channel will short-term failed. At this moment, corresponding data can not acquire, just as the Figure. 6 showing.

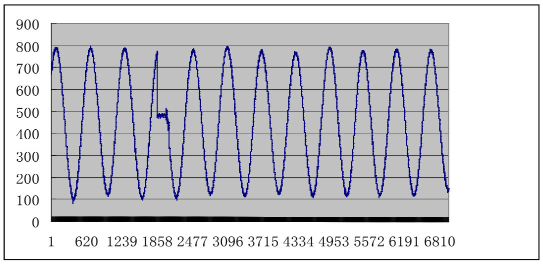
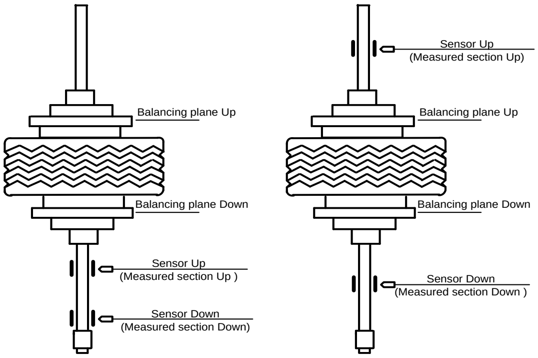


Figure 6 : Signal Obtained When Sensor Failed

The abnormal signal in Figure. 6. is obtained within the period of none force loaded on the sensors. The sensor can not acquire a normal vibration signal at the moment, so the phenomenon is called the short valid of sensor.

According to the positional relationship between the object will to be measured and the support, double-sided balancing machine is usually divided into the Charpy structure and overhanging structures shown in Figure.7. Reduced as much as possible the distance between the measuring surface and balancing planes from the design of structural can make the Charpy structure approximation in unrelated model (the model that measuring surface coincides with balance surface). Reduced as much as possible the distance between the measuring surface and balancing planes, and increased the distance of the two measuring surfaces can play better effect in the inhibiting the changes of association effect which caused by the sensor sensitivity. While in the tire dynamic balancing test system, due to the size constraints of the tire itself, the distance between the two measurement plane is generally fixed, so the source from the mechanical design should reduce as far as possible the associated effects of the sensor, in order to ensure the accuracy of the measurement and get better results of plane separation. In order to ensure the stable vibration center, Hu Qinghan which comes from Shanghai Jiao Tong University, bases on the instantaneous sports center concept of theoretical mechanics, makes up two series of four institutions vibration system which making use of the flexible hinge. It has greatly increased the plane separation and sensitivity of the system, sharply reduced the permissible minimum residual unbalance [9-11].



(a) Overhanging structure (b) Charpy structure

Figure 7 : Overhanging Structure And Charpy Structure

Figure 8 : The Marking Positions Of The Different Tests

Considering sensor correlation effects, based on the corresponding equations, the system has been indirectly calibrated. It greatly improved the zero correction results, just as shown in Table 3. Figure.8. shows the final marking locations of the unbalance. When measured the same tire for many times, the marking results are still relatively concentrated. This proves that the stability of this system is good and feasible.

5. CONCLUSIONS

This paper analyzes the key issues of the sensor selection, installation and use process, focusing on the influence of sensors nonlinearity and associated effect on the test accuracy. Based on abnormal signals obtained from the engineering practice, as well as field testing calibration data, get the following conclusions:

(1) During the sensor preload process, the force of each channel should be mutually independent and unrelated. Otherwise it may lead to short-term failure of the sensor or can not get data in such short period.

(2)Considering the influence of the sensor nonlinear, during the calibration process of the tire balancing test system, it should control the test weight within the linear measurement range of the sensor. Based on the experiment results, the calibration weight of semi-steel tire model is determined to be 50g, and 100g is the best test weight for steel tire model.

(3) As the sensitivity of sensors can not be identical during actual application, changes due to the associated effects of the force will cause inconsistent variable which is to be produced by the unbalance. Thereby, it will reduce the accuracy of the plane separation. The model should be approximation to the non-associated model when design the mechanical structure. In practical applications, it should fully consider the impact of the correlation effects. The experimental results have greatly improved when considering the related effect.

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