Development of Large-Range Dynamic Three-Component Sensor

Jixin Chai, Kexing Chen, Yinming Zhao, Jian Xu and Xiaoyan Fan
The Changcheng Institute of Metrology & Measurement in Beijing, AVIC. Beijing 100095, China
Email: chaijixin@sohu.com

Abstract. Currently, the vast majority of sensor applied in the field of dynamic testing is piezoelectric sensor. Piezoelectric sensors over 200t are very difficult to produce. However, the traditional strain sensor is not suitable for dynamic testing due to its insufficient frequency response. The large-range strain type dynamic three-component force sensor developed in this paper has been successfully applied in high-speed rail collision test experiment, which breaks the monopoly of piezoelectric sensor in the field of dynamic test and has a broad application prospect.

1. Introduction
In the process of train crash safety development and test, in order to study and improve the crashworthiness of the train, it is necessary to measure the distribution of the impact force of the train body, analyze the influence of the structure and stress state of the collision site during the collision, so as to provide a test basis for the design and optimization of the train body. Train collision force wall used to measure the high-speed train collision test data of the moment of collision impact and collision force distribution, analysis of the test vehicle front structure and energy absorption process, research and development for the safety of the train body provides basic data and experimental basis, to improve the train body structure crashworthiness and the computer collision simulation model validation has important research significance.

All the sensors used in the car crash test are piezoelectric sensors imported from abroad, and the collision sensor of KISTLER company is also used in the train crash test (Qingdao sifang), but the imported piezoelectric sensor needs to be customized for a range above 200t, which is expensive and has a long manufacturing cycle.

Domestic piezoelectric sensor (Jiangsu Lianeng) can only achieve 200t, unable to meet the requirements of train crash test. However, the traditional strain sensor has insufficient frequency response, so it is not suitable for dynamic testing.

The Changcheng Institute of Metrology & Measurement in Beijing, AVIC, Through structural design, material selection and other work, the four column multi-component sensor developed by The Changcheng Institute of Metrology & Measurement in Beijing, AVIC has the characteristics of large measuring range, small volume, high frequency response (greater than 8kHz), etc. Through the verification of the National Engineering Laboratory of high speed railway construction technology of Central South University, it can meet the requirements of train collision dynamic test. On this basis, the 200t three component dynamic force sensor developed by the Institute has successfully completed the collision test of the train energy absorbing device provided by CRRC Changchun Railway Vehicles Co., Ltd. for Boston Metro.
2. Development of Large-Range Three-Component Sensor

2.1. Selection of Three Component Sensor
Most of the dynamic force sensors used in the car crash test are single-component piezoelectric sensors. In fact, whether it is a car crash or a train crash, the instantaneous impact force is a spatial force, that is, in addition to the impact force in the main direction $F_z$, there are also impact forces in the two lateral directions $F_x$ and $F_y$. If a strain sensor can measure the impact force in these three directions at the same time, it will greatly improve the accuracy of train crash tests and will be a new breakthrough in the field of high-speed rail tests. Therefore, in this project, we selected a four-column strain sensor capable of simultaneously measuring forces in three directions with excellent performance indexes from a variety of force sensors in the production line and combined with the testing requirements of the train collision wall for theoretical analysis of dynamic performance, the schematic diagram of sensor appearance is shown in figure 1:

![Figure 1. Schematic diagram of strain type dynamic force sensor](image)

2.2. Structural Design of Four - Column Sensor
The integrally machined four-column load sensor is a qualitative leap forward in structural design, manufacturing process and nonlinear compensation technology of the column load sensor. A spherical or spherical bowl is machined in the center of the elastic element roof to introduce the external load under test. At the same time, with the help of ANSYS finite element software and modeling and simulation of the four-column structure, we spread the distance of the four columns to the most appropriate distance on average, so as to enhance the bending moment of inertia and avoid the concentrated moment of inertia caused by the four columns being too close to each other and the deflection of elastomer increased by the columns being too far away.

2.3. The Technology of Sticking Strain Gauge to Sensor and the Technology of Composing Bridg
In order to improve the anti-deflection capacity and measuring stability of the sensor, and to make the strain gauge can evenly feel the stress-strain characteristics of each rod evenly, the main direction force is measured by using multi-strain gauge through single column and different column bridge to realize the sensor self-decoupling. By using the strain gauge on each column to form a bridge, a sensor is formed for each column, and then four sensors are connected in parallel to reduce the coupling error and quadrangle error. The lateral force is measured by means of a double-arm beam with four post patches, which greatly improves the performance of the sensor. The model and patch diagram of the four-column sensor are shown in figure 2:

![Figure 2. Model and patch diagram of the four-column sensor](image)
2.4. Compensation Technology for Strain Sensors
In order to improve the measurement accuracy of the sensor, the compensation technology of the circuit should be applied to realize the high accuracy and high stability measurement of the sensor by means of temperature compensation, creep compensation, nonlinear compensation and sensitivity compensation. The most important one is temperature compensation, followed by creep compensation and sensitivity compensation. The compensation diagram of sensor circuit is shown in figure 9:

2.5. Theoretical Analysis of Dynamic Performance of Strain Sensor
The mesh for the elastomer in the four-column three-component sensor was created by finite element software according to the following figure.
Taking the elastomer of 2000kN sensor as an example, after fixing the bottom end, the static load of 2000kN, 500kN and 500kN is applied to the three directions of the upper plate XYZ at the same time. The resulting elastomer displacement is shown in the list on the right of the figure below.

The resonance frequency of the sensor is the frequency that the sensor is easy to vibrate when it is disturbed. Its deformation under the resonance frequency is the main vibration mode, also known as the mode shape. The resonance frequency of the sensor was calculated by using finite element software. The loading model was shown as follows:
The obtained vibration modes are shown in the figure below:

![Loading model of the sensor](image)

**Figure 6. Loading model of the sensor**

![Vibration modal analysis results of the sensor](image)

**Figure 7. Vibration modal analysis results of the sensor**

According to the theoretical calculation and measured results, the resonant frequency of this type of sensor is higher than 8kHz, which can meet the frequency range requirements of the force measurement system in the project.

### 3. Field Test Verification of Three Component Strain Sensor in Train Collision Test

The 2000kN three-component strain sensor developed by us has been tested and verified in the field of train collision in Central South University. At the same time, the American ARA consulting company also participated in the test. The following are the test photos on site.
The collision wall in the field test is composed of two 2000kN three-component strain sensors and two 2000kN piezoelectric sensors. The field test results show that the difference between the collision force measured by the force sensor and the force measured by the high-speed camera impulse is only 2%. The test curves of the three-component strain sensor and the piezoelectric sensor are shown below:

By the test results can be seen, due to Charge leakage of piezoelectric sensor, two sensors are not back to zero, and strain sensor back to zero is very good, at the same time it can be seen that the strain sensor frequency and dynamic response of a piezoelectric sensor is similar, and the strain sensor measuring the impact force of three directions at the same time. It can be concluded from the
experimental verification that the four-column strain sensor developed by us can completely replace
the piezoelectric sensor for the test of train collision, and the performance index is higher, which will
be a new breakthrough in the field of dynamic test of strain sensor.

4. Application Prospect and Benefit Analysis

China's high-speed railway has developed rapidly in recent years, and the operating mileage of
high-speed railway has reached the first in the world. China's high-speed rail plays a leading role in
the export of China's high-tech industry, which will surely drive a large number of high-tech industries to
take off, which is of great significance and far-reaching influence. The rail vehicle crash test is the
most direct and effective method to evaluate the safety performance of rail vehicle. The load wall is an
important tool for the analysis and design of the crashworthiness of railway vehicles in the crashworthiness test. With the rapid development of rail vehicles, the passive safety performance of
rail vehicles requires a large number of energy absorption components and vehicle crash tests to verify,
but the rail vehicle industry in China currently lacks testing and testing equipment, especially the
large-range force measurement system.

Due to the dynamic and instantaneous nature of vehicle collision and train collision, the required test
sensor must have excellent dynamic performance. Piezoelectric sensor has always been the first choice
in the field of vehicle collision test due to its advantages in measuring principle. At present, most of
the world's piezoelectric sensor manufacturers are in Europe. And even the sensors used in China's
own collision walls are almost entirely imported. However, in the traditional concept, people always
believe that the dynamic performance of strain sensors cannot meet the requirements of automobile or
high-speed rail crash tests. The four-column three-component sensor developed by us has been
carefully designed in terms of structure, sticking strain gauge, composing electric bridge and circuit
compensation. It is proved that the four-column sensor has good dynamic performance through
experiments, and the accuracy and stability of the measurement are beyond comparison of
piezoelectric sensors. Therefore, the four-column and three-component strain force sensor can not only
completely replace the piezoelectric sensor for the train collision test, but also greatly improve the
accuracy of the collision test. This will be a major breakthrough in China's high-speed rail testing and
even the whole dynamic measurement field, and will provide a strong guarantee for China's
high-speed rail to go global.

5. Concluding Remarks

In this paper, a large range dynamic three-dimensional force sensor is developed. The dynamic
response frequency can reach 8kHz, which provides accurate data support for improving the passive
safety and reliability of high-speed trains, this is not only a new breakthrough in the application of
strain sensors in the field of dynamic testing, but also breaks the monopoly of foreign sensors in the
field of collision testing. In the future, it can be applied to the thrust test of aeroengine, the test of
weight and center of gravity of fighter aircraft, the landing gear drop vibration test, the field test of
solid/liquid rocket engine, and the collision test of ship, etc., and has a very broad application prospect.

6. References

[1] TAO Bao qi, WANG Ni. Resistance Strain Sensor. National defense industry press, 1993.
[2] CUI Wei na, WANG Wei. A New Kind of Underwater Robot Six - Dimensional Wrist Force
Sensor [J]. Journal of Instrumentation, 2001, 22(4): 388-390.
[3] MENG Xiang wei, GAO Xue ping. Contact Measurement of Six Freedom for Naval Tank [J].
Journal of Ship Mechanics, 2010, 14(4): 379—384.
[4] ZHU Wen wei, XIE Guo quan. Design and Manufacture of Strain Triaxial Force Sensor [M].
Shanghai Jiao Tong University, 1982
[5] XU Ping, ZHANG De hong, SHAO Heng, YAO Shu guang. Design Method of Large-Tonnage
Load Cell Wall with Comaposite Support Struture for Rail Vehicles[J].Journal of Railway
Science and Engineering, 2017, 14(11):2436-2443
[6] ZHENG Zu dan, HU Wei qiang, Wu Bin. Development of Load Cell Barrier[J]. Shanghai
Automobile, 2011, 1(10): 22–27.