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Research on Automotive Dynamic Weighing Method Based on Piezoelectric Sensor

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Abstract: In order to effectively measure the dynamic axle load of vehicles in motion, the dynamic weighing method of vehicles based on piezoelectric sensor was studied. Firstly, the influencing factors of the measurement accuracy in the dynamic weighing process were analyzed systematically, and the impacts of road irregularities and dynamic weighing system vibration on measurement error were discussed. On the basis of the analysis, the arithmetic mean filter method was used in the software algorithm to filter out the periodic interference added in the sensor signal, the most suitable n value was selected to get the better filtering result by simulation comparison. Then, the dynamic axle load calculation model of high speed vehicles was studied deeply, based on the theoretical response curve of the sensor, the dynamic axle load calculation method based on frequency reconstruction was established according to actual measurement signals of sensors and the analysis from time domain and frequency domain, also the least square method was used to realize the identification of temperature correction coefficient. A large amount of data that covered the usual vehicle weighing range was collected by experiment. The results show that the dynamic weighing signal system identification error all controlled within 10% at the same temperature and 60% of the vehicle data error can be controlled within 7%. The temperature correction coefficient and the correction formula at different temperatures ranges are well adapted to ensure that the vehicle temperature error at different temperatures can also be controlled within 10% and 70% of the vehicle data error within 7%. Furthermore, the weighing results remain stable regardless of the speed of the vehicle which meets the requirements for high-speed dynamic weighing.

Key words: Road engineering; Dynamic weighing; Frequency reconstruction; Piezoelectric-film sensor; Parameter identification

Classification No.: **U492**.8 **Literature code**: A

1 Introduction

Traffic stream axle load information is essential for road safety and road service life. Statistical data show that 70% of road safety accidents are caused by oversize and overload of vehicles [1]. Axle load information can be used to automatically identify overload vehicles, so as to prevent from damage of bridge and road surface caused by overload vehicles. Additionally, axle load information can be used to realize long-term accumulation of road service performance data. Axle load measurement when automotive is normally driving in road is a global problem. Among the common dynamic weighing detectors, piezoelectric sensor has increasingly become the research direction of automotive dynamic technology due to its advantages such as small size, small pavement incision, low maintenance workload, concealing incision, etc.

When dynamic weighing is conducted, the precision of dynamic weighed results can be affected seriously by such randomly uncertain factors as very short action time (within dozens of ms) of tyre on piezoelectric sensor, the force of axle weight on piezoelectric sensor, as well as disturbing force caused by many factors including vehicle speed, vehicle vibration, road disturbance, tyre force, etc. [2-3].

In this article, we firstly systematically analyzed factors affecting measuring accuracy in the course of automotive dynamic weighing, and deeply studied the calculation model of high-speed vehicle dynamic axle load. Additionally, analysis was conducted in the aspects of time domain and frequency domain based on the theoretical response curve and actual measurement

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signal of sensor, so as to establish calculation method based on frequency reconstruction, and to realize identification of system parameters by a multitude of actual measurement data and by means of least square method.

2 Analysis of factors affecting the measuring accuracy in the course of automotive dynamic weighing

Vehicle dynamic weighing refers to automotive weighing when automobile keeps the current motion status. When dynamic weighing is conducted, vehicle which moves through weighing sensor at a certain speed not only can be weighed truly due to the complexity of automotive motion, but also the true weight of vehicle can be easily to be covered by various interference caused by complexity of automotive motion. Automobile is the main body of dynamic vehicle weighing system. It has quite complex motion; especially the motion in the course of dynamic weighing is more complex. The main reasons that caused complex motion are as follows:

(1) Automobile is a complex multivariant power system. The motion status and power characteristics of automobile in the course of dynamic weighing can be objectively and comprehensively described through at least more than 20 degrees of freedom. Therefore, simplified model is generally used in actual analysis.
(2) The reasons of automobile vibration is quite complex. The vibration is the primary motion form affecting weighing in the course of dynamic weighing. While the reason resulting in automobile vibration is quite complex, for example, automobile motor, tyre elasticity, uneven road surface, etc. are all the reasons which result in automobile vibration.
(3) The forms of vibration load are diverse. The complexity of automobile vibration also causes diversity of ground load from automobile. Ground load from automobile mainly covers three kinds of forms including stable load, random load and impact load. The generation of all of these loads comes with great uncertainties.

In a word, the measurement error occurred in automobile dynamic measurement are mainly associated with all kinds of vibrations.

2.1 Measurement error of automobile forced vibration resulting from unevenness of road surface

The unevenness of road surface is the main factor resulting in automobile vibration. Therefore, firstly the vehicle random vibration caused by the unevenness of road surface shall be analyzed to determine the influence of the unevenness of road surface on measurement error. Given the condition that the connection form between cargo and vehicle body is not considered, the automobile vibration model can be simplified as shown in figure 1:

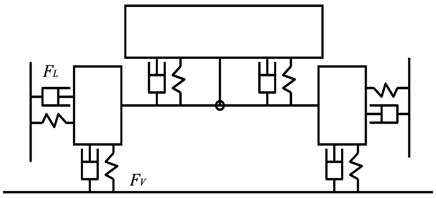


Fig .1 Simplified Model of Automobile Vibration

Where FV refers to the vertical force of tyre, FL refers to the lateral force of tyre. Where, the formula of the vertical force of tyre, is as follows:

$$F_V = \begin{cases} K_V \cdot \delta^e + C_V \cdot \overset{o}{\delta}, \delta > 0, \\ 0, \delta <= 0 \end{cases} \tag{1}$$

Where, K_V, C_V and e refer to constant, δ refers to vertical deformation of tyre. Generally, e is more than 1, that is tyre is featured by characteristics of hard spring. Additionally:

$$K_L = \min(K_L \cdot \lambda + C_L \cdot \overset{o}{\lambda}, \varphi \cdot F_V) \tag{2}$$

Where, K_L, C_L refers to lateral rigidity and damping of tyre respectively, φ refers to lateral friction coefficient of tyre, λ refers to lateral deformation of tyre. When the lateral force resulted by lateral deformation of tyre is more than lateral adhesive force of tyre, sideslip of tyre occurs, and the lateral force of tyre is equal to the lateral friction force.

The damping of vibration damper is non-linear. Generally, stretch stroke damping is more than compression stroke damping, namely:

$$F_D = \begin{cases} C_{D1} \cdot \overset{o}{v}, \overset{o}{v} \geq 0 \\ C_{D2} \cdot \overset{o}{v}, \overset{o}{v} < 0 \end{cases} \tag{3}$$

Where, C_{D1}, C_{D2} refer to stretching damping and compression damping respectively, and $C_{D1} > C_{D2}$; $\overset{o}{v}$ refers to the relative speed of vibration damper.

From the above two formulas, it can be concluded that the unevenness of road surface will result in relatively serious forced vibration of vehicle, so that error will be conveyed to dynamic weighing system.

2.2 Measurement error resulting from vibration of dynamic weighing system

The measurement error mainly refers to error caused by elastic deformation of dynamic weighing system. The system model is always necessarily simplified as required in actual analysis [14], as is shown in figure 2:

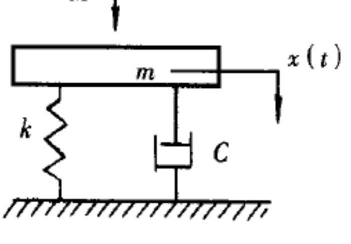


Fig .2 Simplified Model of Dynamic Weighing System

In the figure, *k, C* refer to rigidity and damping coefficient of weighing system, *M* refers to vehicle mass, *m* refers to mass of weighing table, *x* refers to displacement of weighing system. Then, the kinetic model of dynamic weighing system can be represented as follows:

$$(M+m)\cdot\ddot{x}+C\cdot\dot{x}+k\cdot x=Mg\cdot u(t) \tag{4}$$

Where, $u(t)=\begin{cases}0, t<0\\1, t\geq 0\end{cases}$, the load of weighing sensor can be obtained as follows:

$$F(t)=Mg\cdot\left[1-\frac{e^{-\varsigma\omega_n t}}{\sqrt{1-\varsigma^2}}\right]\sin(\omega_d+t+\varphi) \tag{5}$$

Where, undamped natural frequency $\omega_n=\sqrt{\frac{k}{M+m}}$, damping coefficient $\varsigma=\frac{c}{2\sqrt{(M+m)\cdot k}}$, damped oscillation frequency $\omega_d=\omega_n\sqrt{1-\varsigma^2}$, phase angle $\phi=\arctan\frac{\sqrt{1-\varsigma^2}}{\varsigma}$.

Consequently, the difference between the sensor output resulted from vibration and true value is as follows:

$$e=\frac{Mg\cdot e^{-\varsigma\omega_n t}}{\sqrt{1-\varsigma^2}}\cdot\sin(\omega_d t+\varphi) \tag{6}$$

In accordance with mode of integral or average of repeated sampling generally adopted in dynamic weighing, the absolute error can be represented as follows:

$$e=\frac{1}{\tau}\int_0^\tau e\,dt \tag{7}$$

Where, $\tau=l/v$ refers to sampling time, l refers to length of sensor, v refers to vehicle speed. If the worst phase is considered, namely $\phi=90^o$, the relative error will be as follows:

$$\delta=\frac{e}{Mg}=\frac{ve^{-\varsigma\omega_n t}}{l\omega_d\sqrt{1-\varsigma^2}}\sin(\omega_d\cdot l/v) \tag{8}$$

From the above formula, it can be concluded as follows:

(1) With the increase of speed, dynamically affected relative error gradually increases.

(2) Installation site of piezoelectric sensor and rigidity difference asphalt pavement materials result in not large error, but the evenness of road surface greatly affects dynamic relative error.

(3) As for mechanical vibration error of weighing system, the relative error is associated with vehicle weight. The larger the vehicle weight is, the larger the relative error is.

3 Research on calculation model of high-speed vehicle dynamic axle load

For calculation of vehicle dynamic axle load, axle load signal shall be required to be analyzed, interference factors shall be removed, so as to conduct mechanism modeling, and identify model parameters. The vehicle weight will be obtained, and the results will be analyzed and verified.

3.1 System model

When piezoelectric material is forced by external force in some direction, deformation occurs, which results in the relative displacement of positive and negative charge center inside the material to generate polarization, so as to result in positive and negative bound charge occurring on the relative surface of the material. When the external force is small, piezoelectric material restores to the uncharged status, which is called piezoelectricity or direct piezoelectric effect. The sensor manufactured according to piezoelectricity is called piezoelectric sensor. As vehicle moves through piezoelectric sensor, sensor generates charge signal due to tyre impact. The charge signal is converted into voltage signal after it is amplified, and the amplitude variation of voltage signal is directly proportional to the pressure applied by tyre on the sensor, the circle of signal is correlated to time of tyre staying on the sensor.

The width of signal waveform is correlated to vehicle speed, the faster the speed is, the shorter the time of tyre staying on the sensor is, and the narrower the signal waveform (as is shown in figure 5), the smaller the area between signal waveform and transverse axle. But the product of the area and the corresponding speed does not change, that is, the value is a constant directly proportional to vehicle load.

$$W=A\cdot v\cdot C \tag{9}$$

Where, *A* refers to area of hook face, *v* refers to vehicle speed, *C* refers to adjustment coefficient. They can be determined by test that the vehicle whose weight is known moves through sensor. The vehicle weight can be obtained through multiplying the three.

Furthermore, it can be seen that speed measurement error is directly proportional to axle load measurement error. The more stable the vehicle speed in driving is, the more accurate the measured axle load is.

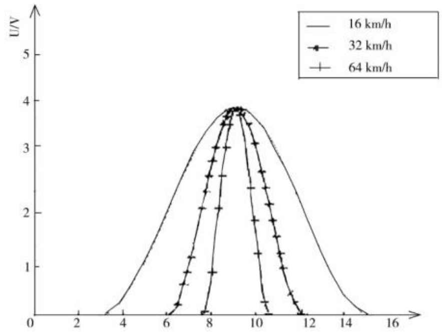


Fig .3 Calculating Schematic Diagram of Charge Dynamic Weighing System

Pretreatment of filtering wave for signal has been conducted in the previous research to basically eliminate the influence of periodic interference. Then the random error interference caused by such factors as filtering vehicle vibration, filtering unevenness of road surface, etc. will be researched.

3.2 Time domain analysis

The actual action of vehicle weight on sensor is the effect of rectangular pulse overlapping triangle pulse, as is shown in figure 7:

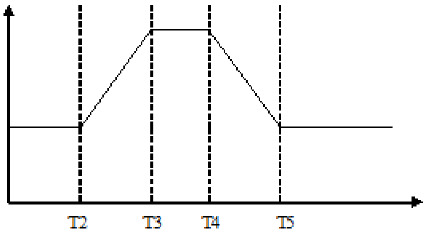


Fig .4 Effect Diagram of Vehicle Weight

Where, the process from T2 to T3 represents the whole width of sensor which is gradually covered by tyre, the time difference is *W*/*v,* where *W* refers to sensor width, *v* refers to vehicle speed. The process from T3 to T4 represents the process from tyre totally covering sensor to tyre which is about to start to leave sensor, the time difference is (*L*-*W*)/*v,* where *L* refers to the touchdown width of tyre. The process from T4 to T5 is opposite to the process from T2 to T3. The actually selected sensor width in the project is 6.6mm, while generally the action area of tyre is 60~100mm. Therefore, theoretically, it is analyzed that the time width of table period shall be about 5 times as long as the tilt period

However, actually the measured output signal of piezoelectric sensor is shown in figure 8. Where blue curve refers to signal when vehicle passes by, red curve refers to signal curve when none of vehicle passes by. It can be seen that the table period theoretically anticipated does not occur in the middle part of blue curve, and the base electrical level of signal curve decreases before and after tyre moves through sensor. The reason is that the natural frequency of piezoelectric sensor and the measurement system composed of the successive amplifying circuit are not infinite, it can be regarded as a band-pass filter. Therefore, the vehicle weight action signal is expanded by measuring system in time domain. While decrease of base electrical level of curve refers to charge signal generated from tangential deformation of sensor resulted from tyre's friction on ground.

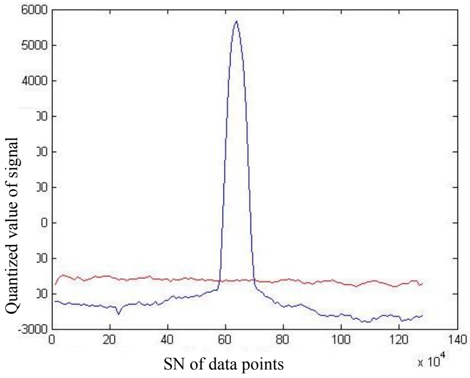
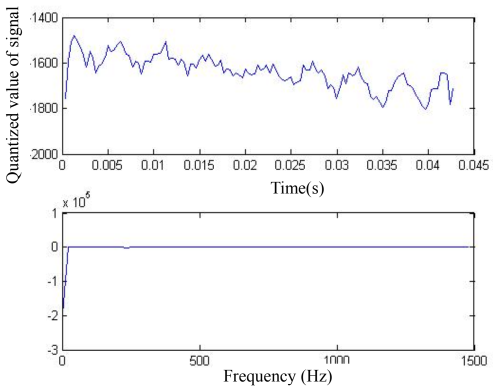


Fig .5 Signal of Piezoelectric Sensor

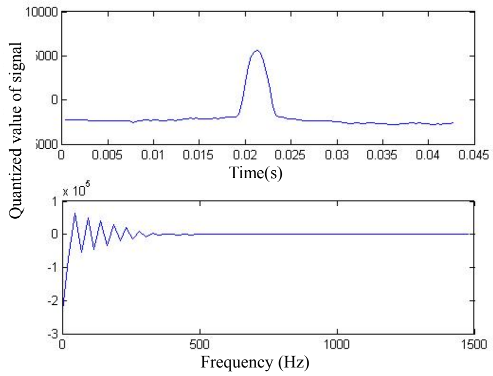
The flat period of signal can not be directly measured, but it can be discovered from careful observation of signal chart that there is a apparent point before signal sharply ascends and after signal sharply declines respectively. Compared driving speed of vehicle with tyre touchdown width, it can be discovered that the distance vehicle moves through in the period is basically in line with theoretical anticipation. Therefore, the interval between the two points includes three stages of T2, T3 and T4, while the total weight of vehicle shall be the sum of acting force of the three stages of T2, T3 and T4.

3.3 Frequency domain analysis

Before eliminating basic offset of frequency domain, frequency spectrum of piezoelectric sensor signal before and after vehicle moves through piezoelectric sensor is firstly analyzed as shown in figure 9. It can be seen that the basic signal is basically thought as direct current quantity, while frequency response of vehicle axle load is also centralized in low-frequency area of less than 300HZ, and direct current component in frequency spectrum of axle load signal is equivalent to that in the basic signal. Therefore, before treating all the frequency spectrum of sensor signal, firstly signal frequency must subtract frequency spectrum of basic signal in frequency domain, so as to filter basic signal.



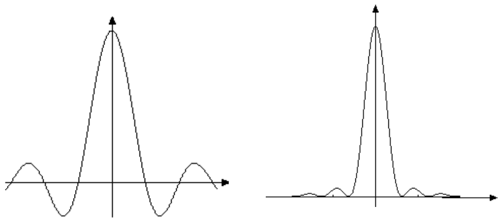
(a) Vehicle does not pass by



(b When vehicle passing by

Fig .6 Time-Domain and Frequency-Domain Graphs before/after Passing

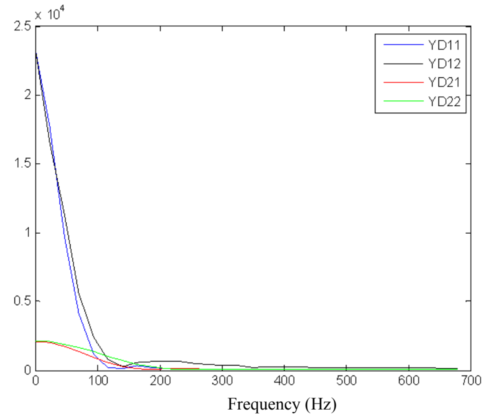
It can be known from time domain analysis that vehicle weight action can be regarded as overlap of rectangle pulse and triangle wave pulse. The expression form of the two kinds of pulses in frequency domain is shown in figure 10:



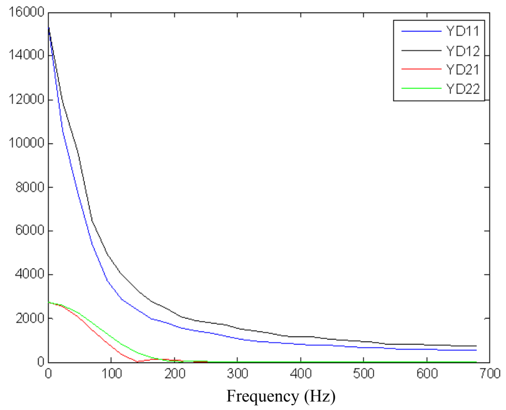
(a) Rectangle pulse (b) Triangle wave pulse

Fig .7 Pulse Spectrum Diagram

Therefore, output signal spectrogram in frequency domain of Piezoelectric Sensor should be similar with Fig.10. A signal spectrum of good original data result can be compared with that of poor original data result, as shown in Fig.11.



(a) Error -8% signal



(b) Error 23% signal

Fig .8 Original Signal Spectrum Diagram

It can be seen from Fig.11 that when the real original signal curve spectrum gets relatively close to the theoretical spectrum, the error is relatively small, while when the real original signal curve spectrum gets relatively far from the theoretical spectrum, the error is relatively big. The reason is that: high frequency errors such as vehicle vibration mingle in low frequency signals of vehicle weight, which thus lead to the variation of signal spectrum. The processing method proposed by former scholars is to process the spectrum of variation through wavelet analysis and neural network scheduling algorithm so as to obtain the most real vehicle weight signals.

3.4 Dynamic Axle Load Calculation Algorithm Based on Frequency Reconstruction

It's found through big quantity of data spectrum diagrams that the difference between real signal spectrum and theoretical spectrum can clearly reflect the magnitude of errors. Therefore, if the real spectrum can be directly corrected based on theoretical spectrum, the errors may likely be reduced. The Dynamic Axle Load Calculation Algorithm Based on Frequency Reconstruction is proposed based on this and as shown in Fig.12, the algorithm description is as follows:

(1). Elimination of basic offset. It can be seen from figure 11 that there is a apparent basic offset on blue and black curve in figure (b), which is most different from theoretical frequency spectrum. Therefore, basic offset is firstly eliminated. The first zero crossing point of signal frequency spectrum can be estimated from vehicle speed. And all the calculated values subtract the value of the zero-crossing point within frequency domain, so that basic offset returns to zero.

(2). Data after the first zero crossing point are sorted, so that the situation of gradually declining in theory is presented in the sequence. If "warped-tail phenomenon" occurs, basic offset will be eliminated according to the second zero crossing point, that is all the calculated values after the first zero crossing point subtract the value of the zero-crossing point.

(3). Repeat the above steps, until the frequency of the zero-crossing point is more than 300HZ.

(4). Data are converted to time domain to be treated by integral, so as to calculate the last vehicle load.

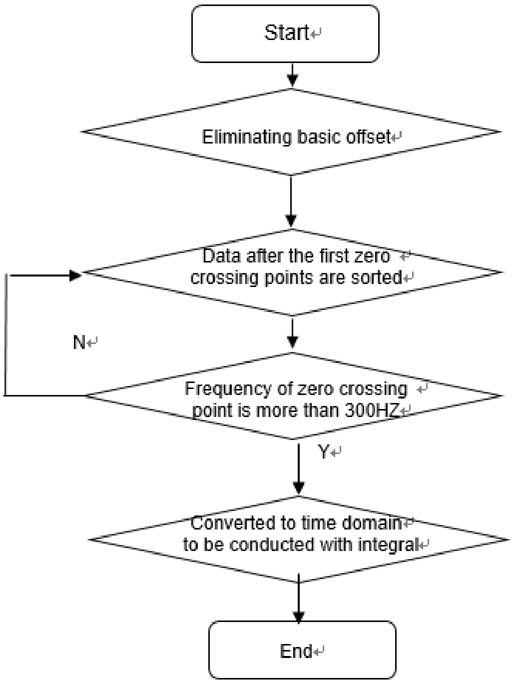


Fig .9 Dynamic Axle Load Calculation Algorithm Based on Frequency Reconstruction

The result of the processed data of Fig.11(b) Original Signal Spectrum Diagram following the above steps is as shown in Fig.13 with the error of -2.38%.

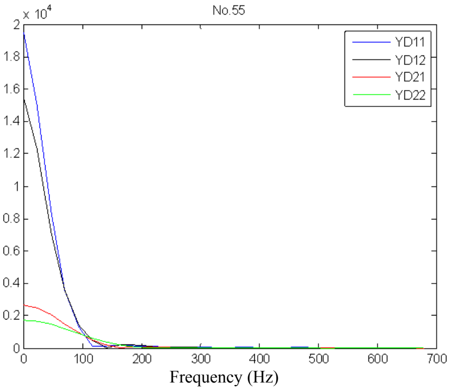


Fig .10 Data after Processing

3.5 System identification

Objective function has been obtained in the aforesaid $W=A\cdot v\cdot C$, therefore the identification issue turns to a least squares issue that solves adjustment parameter C.

Select the least square method for system identification and assume a SISO (single input/output) system, as shown in Fig.14:

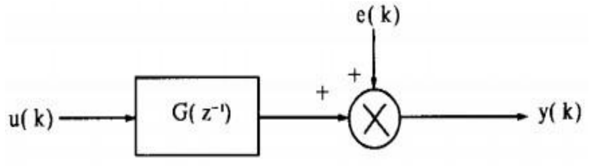


Fig .11 SISO System Structure Diagram

Discrete transfer function is:

$$G(z^{-1})=\frac{B(z^{-1})}{A(z^{-1})}=\frac{b_1z^{-1}+b_2z^{-2}+\ldots+b_nz^{-n}}{1+a_1z^{-1}+a_2z^{-2}+\ldots+a_nz^{-n}} \quad (10)$$

Relation between input and output is:

$$u(k)\cdot G(z^{-1})+e(k)=y(k) \quad (11)$$

It can be further obtained:

$$y(k)\cdot A(z^{-1})=u(k)\cdot B(z^{-1})+e(k) \quad (12)$$

In the formula, disturbance quantity $e(k)$ is an average value, the white noise unrelated with 0.

The above formula is converted into the form of difference equations:

$$\begin{aligned}y(k)&=-a_1y(k-1)-a_2y(k-2)-\ldots-a_ny(k-n)\\&+b_1u(k-1)+b_2u(k-2)+\ldots b_nu(k-n)+e(k)\end{aligned} \quad (13)$$

Assuming:

$$\begin{cases}\phi(k)=\left[-y(k-1) \quad \ldots \quad -y(k-n) \quad u(k-1) \quad \ldots \quad u(k-n)\right]^T\\ \theta=[a_1 \quad a_2 \quad \ldots \quad a_n \quad b_1 \quad b_2 \quad \ldots \quad b_n]\end{cases}$$

The formula can be:

$$y(k)=\phi^T(k)\theta+e(k) \qquad (14)$$

Extending to N inputs and outputs observed value $\{u(k)$, $y(k)\}(k=1,2\ldots N)$. Substituting into the formula to write in matrix form as:

$$Y=\Phi\theta+e \qquad (15)$$

Where,
$$\begin{cases} Y=[y(n+1) \quad y(n+2) \quad \ldots \quad y(n+N)]^T \\ e=[e(n+1) \quad e(n+2) \quad \ldots \quad e(n+N)]^T \end{cases}$$

$$\Phi=\begin{bmatrix} -y(n) & \ldots & -y(1) & u(n) & \ldots & u(1) \\ -y(n-1) & \ldots & -y(2) & u(n+1) & \ldots & u(2) \\ \vdots & \ldots & \vdots & \vdots & \ldots & \vdots \\ -y(n+N) & \ldots & -y(N) & u(n+N) & \ldots & u(N) \end{bmatrix}$$

Functional $J(\theta)$ is:

$$J(\theta)=\sum_{i=1}^{N}(Y-\Phi\theta)^2=\sum e^2(n+i) \qquad (16)$$
$$=e^T\cdot e=(Y-\Phi\theta)^T(Y-\Phi\theta)$$

The principle of the least square method is to minimize $J(\theta)$ to evaluate extreme value and obtain:

$$\frac{\partial J}{\partial\theta}=\frac{\partial}{\partial\theta}[(Y-\Phi\theta)^T(Y-\Phi\theta)]=0 \qquad (17)$$

The least squares value of system can be obtained in such way.

$$\theta=(\Phi^T\Phi)^T\Phi^T Y \qquad ()$$

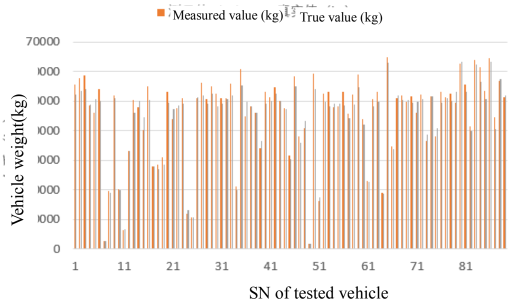
The least squares value of system parameter is obtained in such way.

4 Analysis on system identification result

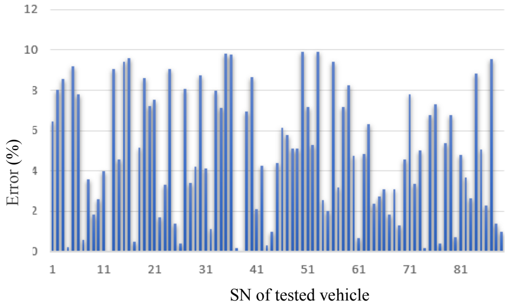
Parameter identification on dynamic weighing data of vehicles with different weights under the state of natural vehicle stream was carried out based on a large number of experimental data. The result is as shown in Tab.1. Full data is not given due to the big data volume. Weights of vehicles cover a range from 2 ton to 55 ton. True value, measured value and error results are as shown in Fig.15.

Tab .1 System Identification Results at the Same Temperature

Plate No.	**Test time**	**Tem pera ture**	**(kg) Measu red value**	**True value (kg)**	**Error (%)**
Yu G738xx	2013/6/22 13:59	23	55531	52160	6.46
YuA1N8xx	2013/6/22 16:16	23	2756	2740	0.58
YuG288xx	2013/6/22 19:31	23	28451	27060	5.14
YuJ768xx	2013/12/10 7:55	-4	51470	51980	0.98
Yu F121xx	2013/12/10 3:56	-3	56760	57560	1.39
Yu J629xx	2013/6/28 12:41	44	59372	54020	9.91
Yu G208xx	2013/6/28 13:04	45	16296	17560	7.19
...	...	...	...	...	...



(a) Measured value and true value



(b) Absolute measurement error

Fig .12 Dynamic Weighing Results at the Same Temperature

Results show that all of the errors of the vehicle data under the state of natural vehicle stream after system identification are controlled within 10% and 70% of vehicle data errors are within 7%. No matter how fast or slow the vehicle passes, the weighting results remain stable regardless of the speed of the vehicle which meets the requirements for high-speed dynamic weighing.

5 Conclusion

The automotive dynamic weighing technology based on piezoelectric sensor was researched in this thesis. Analysis was performed in the aspects of time domain and frequency domain based on theoretical response curve and actual measured signal of sensor to establish calculation method on the basis of frequency reconstruction. The identification of correction coefficient was finally realized by means of least square method through a multitude of actual measured data. The results of actual collected data showed that frequency reconstruction algorithm and system parameter identification propose in this article can meet the requirement of high-speed dynamic weighing.

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