Research on Load Collection Technology of Tractor Frame

Shumin Zhu\textsuperscript{1,2,}\textsuperscript{*}, Zhengwen Yuan\textsuperscript{1,2} and Liang Sun\textsuperscript{1,2}

\textsuperscript{1} Jiangsu Xuzhou Construction Machinery Research Institute, Xuzhou, 221004, China
\textsuperscript{2} State Key Laboratory of Intelligent Manufacturing of Advanced Construction Machinery, Xuzhou Construction Machinery Group, Xuzhou, 221004, China
\textsuperscript{*}380778350@qq.com

Abstract. A convenient and feasible tractor frame external load collection technology is proposed in this paper. Based on the frame structural and force characteristic, the sensors for the load measurement are designed, and the mathematical relationship between the loading force and the sensor output voltage and the displacement signal is obtained. On this basis, the theoretical calculation model of the frame external load is established. Based on the dynamic test load spectrum data of the frame, the virtual strain at the locations \(L_1\) and \(L_2\) is obtained through simulation. The comparison between the virtual strain and the actual strain shows that the frame external load data is reasonable, which proves that the load collection technology is credible and can provide data support for tractor design and optimization.

1. Introduction

The tractor is a commercial vehicle with special equipment for towing semi-trailers, which is the main vehicle for road freight transportation. The frame is one of the important parts of the tractor, which connects the components as a platform and affects the frame overall performance\cite{1-6}. During transportation, the frame mainly bears the static load of the components and the dynamic load generated by road, so that the frame is prone to fatigue damage, which reliability is highly concerned by people\cite{7-9}.

In this paper, the tractor frame is used as the object. Based on the in-depth analysis of the frame structural and mechanical characteristics, a practical and systematic engineering method for measuring the frame external load is proposed. According to the scheme, the push rod and the pull rod force sensors for the load test are designed, which are arranged on the frame. The relational expressions between the loading force and the sensors output signals are obtained in the laboratory. On this basis, the theoretical calculation model of the frame external load is established, which accuracy is verified through the comparison of the simulation and the measured data. According to the theoretical theory model of the external load, the dynamic external load of the tractor frame can be obtained at any time, which can solve the problem that the external load is difficult to measure during the practical work of the tractor frame.

2. Load Collection Technology Program

2.1. Overview of the overall structure of the tractor and the force analysis of the frame

The tractor structure is reasonably simplified, which is mainly composed of the frame (such as the longitudinal beam 1, the second beam 2, connecting plates) and the fixed parts (such as the cab, engine,
saddle, gearbox and fuel tank) and the connectors, as shown in Figure 1, the components are the front axle 3, the front axle leaf spring 4, the middle axle 5, the pull rod 6, the balance suspension 7, the rear axle 8, the rear axle leaf spring 9, the push rod 10, the tires and others.

Figure 1. Tractor frame (a) and enlarged view of partial structure (b).

During the transportation, the frame is in a dynamic force balance state under the action of the vertical downward static load generated by the fixed parts, the dynamic excitation load of the tire and the ground on the frame upward and the inertial force. In order to analyse the dynamic load balance of the frame, it is necessary to obtain the ground-to-frame dynamic excitation load. Define the frame external load as $F$, which can be written as:

$$
F = \begin{bmatrix}
F_1, F_2, \ldots, F_{12}
\end{bmatrix}
$$

(1)

Where $F_1$ and $F_2$ are the loads of the front axle acting on the front axle leaf spring; $F_3, F_4, F_5$ and $F_6$ are the loads of the pull rod acting on the leaf spring block; $F_7, F_8, F_9$ and $F_{10}$ are the loads of the push rod acting on the leaf spring block; $F_{11}$ and $F_{12}$ are the loads of the rear axle leaf spring acting on the spring block. As shown in Figure 2.

Figure 2. Schematic diagram of the frame external load.

2.2 Sensor design and calibration

2.2.1 Design and calibration of push rod and pull rod force sensors

The pull rod and the push rod are mainly subjected to the axial pull-push type load in the actual transportation. As shown in Figure 3, the strain gauges $R_1, R_2, R_3$ and $R_4$ (resistance value: $120 \pm 0.3\Omega$) are arranged along the surface of the rod, which are combined to form a Wheatstone full bridge. The $R_1$ and $R_4$ are along the rod axial direction, and the $R_2$ and $R_3$ are along the rod lateral direction. $R_4$ and $R_3$ are symmetrically arranged with $R_1$ and $R_2$. 


Figure 3. Sensor strain gauge arrangement (a) and Wheatstone full bridge (b).

Under the excitation voltage $U$, the output voltage $\Delta U$ is as shown in the formula (2).

$$\Delta U = \frac{1 + \mu}{2EA} KUF_s$$  \hspace{1cm} (2)

Where $K$ is strain gauge sensitivity coefficient; $A$ is cross-sectional area at the location of $R_1$ and $R_4$; $\mu$ is Poisson's ratio; $E$ is material elastic modulus. In order to make $F_s$ calculation convenient, the force sensors are usually calibrated in the laboratory, and the linear relationship between the load and the output voltage which can be obtained by calibration experiment is

$$F_s = a \times \Delta U + b$$  \hspace{1cm} (3)

Where $a$ and $b$ are the experimental calibration coefficients.

2.2.2 Leaf spring calibration experiment

According to the relevant standards, the front axle leaf spring and the rear axle leaf spring of the tractor are calibrated in the laboratory as shown in Figure 4. The relationship between the leaf spring deformation displacement $\delta_D$ and the loading force $F_{\text{Loading}}$ is obtained as shown in formula (4).

$$F_{\text{Loading}} = k \times \delta_D + c$$  \hspace{1cm} (4)

Where $k$ is the leaf spring stiffness and $c$ is the calibration factor.

Figure 4. Calibration experiment of the front axle leaf spring (a) and the rear axle leaf spring (b).

3. Theoretical Calculation Model of External Load

The external loads (from $F_3$ to $F_{10}$) can be easily obtained through the force sensors calibration formula, as shown in the formula (5).

$$F_i = a_i \times \Delta U + b_i \quad (i=3, 4, \ldots, 10)$$  \hspace{1cm} (5)

Where $a_i$ and $b_i$ are the constant calibration coefficients.

For the external loads ($F_1$, $F_2$, $F_{11}$ and $F_{12}$), it is necessary to measure the deformation displacement of the leaf spring by the displacement sensor. For example, in the analysis of the rear axle leaf spring force, a displacement sensor is arranged at each of the left and right sides of the leaf spring to measure the deformation of the leaf spring in the vertical direction. The simplified diagram is shown in Figure 5. The highest point of the leaf spring is regarded as a fixed point. P1 is regarded as the original state of
the leaf spring without force. P2 is regarded as the state of the leaf spring under the standard test material, and P3 is regarded as the state of the leaf spring under actual transportation. \( \delta_0 \) is the initial displacement value measured by the right displacement sensor under the standard test material, and \( \delta \) is the displacement value measured by the right displacement sensor during the actual transportation.

Figure 5. Schematic diagram of the force calculation model of the leaf spring.

According to the leaf spring calibration formula (4), the load \( F_R \) of the rear axle acting on the right side of the leaf spring can be calculated as shown in the formula (6).

\[
F_R = k \times (\Delta_0 + \Delta') + c
\]  

(6)

Through the formula (7), the formula (6) can be re-written as:

\[
F_R = -k \times \delta + (k \times \Delta_0 + k \times \delta_0 + c)
\]  

(7)

Where \( \Delta_0 \) is the deformation value of the leaf spring when the tractor is equipped with standard test materials, and \( k \Delta_0 \) represents the weight of the leaf spring suffered when the tractor is equipped with standard test materials, which can be measured by the weighbridge; \( \delta_0 \) and \( c \) are also the constants. The equation (8) can be written in simpler forms as:

\[
F_R = -k \times \delta + C
\]  

(9)

Where \( C \) is a constant. Similarly, the load \( F_L \), which is the force of the middle axle applying to the right side of the leaf spring, can be calculated as shown in formula (10).

\[
F_L = -k \times \delta' + C'
\]  

(10)

The force of the rear axle leaf spring acting on the frame can be simplified as a concentrated force \( F_{11} \) and \( F_{12} \), which can be calculated by equation (11).

\[
F_j = -\frac{k_j}{2} (\delta + \delta') + \frac{1}{2} (C + C') \quad (j=11, 12)
\]  

(11)

Where \( k_j \) is the stiffness value of the rear axle leaf spring; \( \delta \) and \( \delta' \) are the displacement values measured by the displacement sensors; \( C \) and \( C' \) are constants.

According to the characteristics of the front axle leaf spring (the physical diagram is as shown in Figure 6), the deformation displacement amount of the central spring can be measured by one displacement sensor. The calculation expression of the loads \( F_1 \) and \( F_2 \) can be obtained by referring to equation (9), as shown in formula (12).

\[
F_{w} = -k_w \times \delta + C'' \quad (w=1, 2)
\]  

(12)

Where \( k_w \) is the stiffness value of the front axle leaf spring, and \( \delta \) is the displacement value measured by the front axle leaf spring displacement sensor, and \( C'' \) is a constant.

The theoretical calculation model of the frame external load \( F \) is established.

4. Verification of Theoretical Calculation Model of External Load

The dynamic test is carried out in a standard test site, and the sensor signals are collected throughout the process. According to the test requirements, the modified pull rod and push rod force sensors are
installed in the tractor. Six displacement sensors are installed at the front and rear bridge springs, and two strain gauges \((L1 \text{ and } L2)\) are arranged on the second beam of the frame. As shown in Figure 6.

![Figure 6. Sensors arrangement on the tractor.](image)

A total of 18 output signals are obtained from the test, including 6 displacement signals and 10 voltage signals for calculating the frame external loads and 2 strain signals for verification. The frame external load spectrum is obtained according to the frame theoretical external load calculation model. The finite element model of the frame is created in Hypermesh software, and the unit force load boundary is added to the finite element model, as shown in Figure 7.

![Figure 7. Finite element model of the frame.](image)

The frame finite element analysis result is read into the nCode software. Based on the frame external load spectrum, the virtual strains at the locations \((L1 \text{ and } L2)\) of the second frame beam are obtained through the method of virtual strain in the nCode software, which are compared with the actual test measured strains at the same locations. As shown in Figure 8.

![Figure 8. Comparison of virtual strain and actual strain at the locations L1 (a) and L2 (b).](image)

It can be seen from Figure 8 that the virtual strain curve is highly consistent with the actual strain curve and the relative error between the actual and the virtual strain is less than 7%. The result shows that the external load spectrum calculated by the theoretical calculation model is reasonable, which
can meet the engineering application. It also shows that the accurate load data for design and analysis of the frame can be obtained by this method.

5. Conclusion
In this paper, a convenient and practical measurement scheme of the tractor frame external load is proposed. Combined with the sensor measurement technology, the theoretical calculation model of the frame external load is established. Based on the actual test data of the tractor and the virtual simulation technology, the virtual strain curve at the locations \(L_1\) and \(L_2\) is obtained, which is highly in agreement with the actual test strain and their relative error is less than 7%. It is verified that the tractor frame external load collection technology is feasible and the external load data through theoretical calculation model is credible.

References
[1] Ni Y. (2008) Development power of semi-trailer tractor[J]. Special Purpose Vehicle, 6: 29-32.
[2] Han Zhennan, Gu Yingchun. (2011) Bending-torsional strength analysis and improvement of DL4100 semitrailer tractor frame[J]. Automotive Technology, 4: 22-25.
[3] Xu Maowu, Gao Yuguang. (2013) Lightweight design of a semi-trailer tractor for drop and pull transport[J]. Design and Calculation and Research, 6: 04-09.
[4] Liu E L. (2011) Static and dynamic characteristic analysis of a semi-trailer tractor frame[D]. Taiyuan University of Technology.
[5] Liu J. (2007) Fatigue reliability analysis of a special vehicle frame[D]. Nanjing University of Science and Technology.
[6] Gao H C. (2016) Fatigue analysis and optimization of a heavy truck frame[D]. Beijing University of Technology.
[7] Shi Chaojun, Zhang Shenglan. (2014) Research on lightweight of CNG tractor’s frame[J]. Journal of Hubei University of Automotive Technology, 2: 22-25.
[8] Han Zhennan, Huo Junjie. (2012) Dynamic analysis and improvement of semi-trailer frame[J]. Machinery Design and Manufacture, 7: 159-161.
[9] Zhu Yi. (2009) Finite element analysis of semi-trailer frame[D]. Hefei University of Technology.