

Test on Stress Distribution of Bionic C-leg Wheel-soil Interaction with Its Data Processing

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Abstract. To study the relationship between the ground support force and drawbar pull of C-leg and the normal and shear stress on the wheel flange, while the C-leg of the six-legged bionic sand-based robot travels on the sand base, the integral model of the above relationship are given on the basis of the designed C-leg loop experimental platform. To solve the limitation of sensors, a "position weighted average numerical interpolation method" is proposed. The normal stress and shear stress sensor on the wheel flange obtained corresponding data by experiment. A number of values are inserted between the measured values of the sensors by the "position weighted average numerical interpolation method". The ground support force and drawbar pull are calculated by the given integral model. At the same time, the three-dimensional force sensor installed on C-leg axle measured ground support force and drawbar pull through the test. The relative error of above force calculated from the integral model is 4.69% and 1.16% respectively compared with the mean value measured by the three-dimensional force sensor. The relative error is less than 5%, which verifies the correctness of the integral model and the feasibility of "position weighted average interpolation method".

1. Introduction

In recent years, in order to meet the needs of adventure, rescue, military reconnaissance, lunar surface and Mars surface detection, domestic and foreign scholars have been engaged in extensive research on robots and planets running on soft ground. Among them, the establishment of mathematical model of wheel-soil interaction is one of the hot topics. Shibly et al. [1] gave a simplified equation of the normal stress and shear stress of planetary exploration rover's wheel-soil interaction and an integral model that can calculate its drawbar pull, the ground support force and the wheel-axle resistance torque verified with good accuracy through the single test bench in the dry sand. Considering the limitation of the Bekker model, Meirion and Spenko[2] propounded an improved pressure-sinkage model for a small rigid wheel. Senatore and Iagnemma[3] installed the force sensor on the wheel flange to measure the movement rule between the normal stress force and shear stress force while wheel travelling on dry sand. The above methods used to analyze the wheel-soil interaction belong to the means of terramechanics. In March 2013, a paper on the Journal of Science [4] attracted the attention of academics to a bionic C-shaped six-legged robot. The authors propose the concept and method of terradynamics, which uses the 6-DOF manipulator to manipulate the movement of a small aluminum



plate ($3.81 \times 2.54\text{cm}^2$) in the granular media by means of a three-dimensional force sensor and a torque sensor to test drag force (horizontal direction) and lifting force (vertical direction) of the unit area per unit area at different attack angles and different intrusion angles, and thus calculated the ground support force and the drawbar pull of the C-leg by the wheel-soil interaction model. The authors also show that the C-legs have the best performance on the soft granular media in various heterogeneous robot leg types by calculation and experiment.

This paper will briefly introduce the C-leg loop experiment platform based on the theory of terramechanics, and according to the tested normal stress and shear stress of wheel-soil interaction to study its data processing method. The results of this paper can be used to provide theoretical and technical support for establishing mathematical model of C-leg wheel-soil interaction.

2. Situation of test

2.1 The loop experiment platform

The overall structure of the loop experiment platform is shown in Figure. 1[5]. The mechanical and electrical parts are composed of central column, the supporting connecting rod and the three C-legs on one side with its support structure. The three C-legs on one side are respectively driven by AC servo motor to revolve around the center column. C-leg 3 is used for testing, which installs a 16-way sensor and a digital encoder in total. There are 4 ways for three-dimensional force sensor (with torque measurement) installed on the drive axle of the C-leg to test ground support force, drawbar pull, axial force and resistance torque on axle of C-leg separately. The rest 12 ways are used for 6 sets of sensors installed on the wheel flange, each of which includes a normal stress sensor and a shear stress sensor.

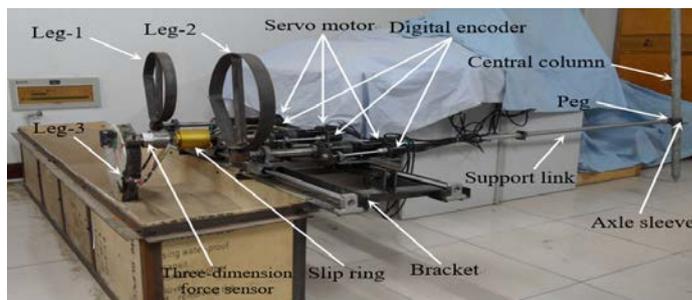
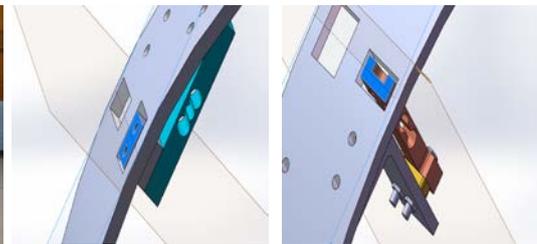


Figure.1 The loop experiment



(a) (b)

Figure.2 Installation of normal and shear stress sensors

The normal stress and the shear stress sensor's installation are shown on Figure. 2. The Figure. 2(a) describes the normal stress sensor installation. Figure. 2(b) describes the shear stress sensor installation.

The radius of C-leg, $R=165\text{mm}$, and the width of C-leg wheel, $b=40\text{mm}$. The weight of C-leg for testing is 2.47kg , and the weight endurance of the tested wheel is 14kg in static state. The material of C-leg is steel plate and the outer wheel is smooth without wheel thorn.

The hardware of data acquisition system is the NI PCI-6143S multi-function data acquisition (DAQ) board card[6]. Two types of tests can be carried out on the platform. One is test experiment of the dynamic characteristics, The other is the test experiment in sand tank: The C-leg is placed in the sand tank, only to limit its advancing, which can complete the test of slip rate of 1. This experiment mainly tests the relationship between the drawbar pull and its relative velocity that taking sand medium as the reference point of C-leg.

2.2. The Sand tank

The overall dimension of the sand tank is $2000\text{mm} \times 400\text{mm} \times 400\text{mm}$. The sand on the sand

tank is taken from the natural aeolian sand of the Tengger desert (dry-sand) , and the sampling site is zhongwei shapo head.

2.3. Testing principle

Figure. 3 portrays the C-leg and sand interaction analysis of forces. The vertical baseline, BD, and the reference line of C-leg wheel, OA, are defined. The rotation angle, θ , displays the displacement of OA relative to BD during the movement of C-leg. Φ denotes the deflection angle of the observation point on the wheel flange relative to the reference line OA (Clockwise rotation angle is positive, the counter clock wise deflection is negative). Φ_1 and Φ_2 are the entry and departure angle respectively. z_1 is the front settlement and z_2 is for settlement. R , b , and a denote the wheel radius width, and round corner of the C-leg respectively.

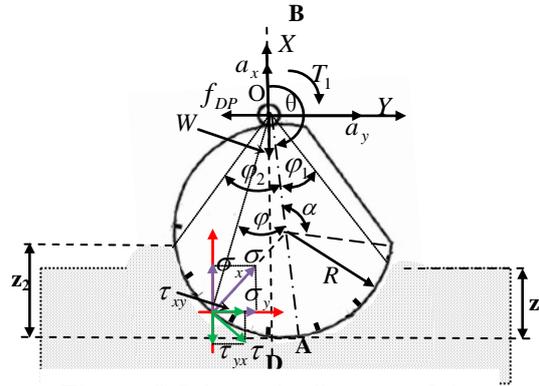


Figure.3 Schematic diagram of the sensor group installation of the C-leg

C-leg movement equations are expressed as

$$F_N(\theta) - W - Mg = Ma_x \quad (1)$$

$$F_{DP}(\theta) - f_{DP} = Ma_y \quad (2)$$

$$T_1 - T_2(\theta) = J \frac{d^2\theta}{dt^2} \quad (3)$$

Here: M and J denote quality and rotary inertia of C-leg, respectively. $F_N(\theta)$ and $F_{DP}(\theta)$ are ground support force and drawbar pull, respectively. X -direction and Y -direction acceleration are a_x and a_y , respectively, and g is acceleration of gravity. T_1 is motor driving torque. $T_2(\theta)$ is resisting torque of wheel-soil interaction.

The ground support force and drawbar pull caused by C-legs' wheel and soil interaction:

$$F_N(\theta) = F_{N\sigma}(\theta) + F_{N\tau}(\theta) \quad (4)$$

$$F_{DP}(\theta) = F_{DP\sigma}(\theta) + F_{DP\tau}(\theta) \quad (5)$$

Here: $F_{N\sigma}(\theta)$ and $F_{N\tau}(\theta)$ are respectively normal stress component and shear stress component of the ground support force. $F_{DP\sigma}(\theta)$ and $F_{DP\tau}(\theta)$ are respectively normal stress component and shear stress component of the drawbar pull.

The integral model of the above components expressed as Eqs. (6) to (9):

$$F_{N\sigma}(\theta) = -2bR \int_0^{\phi_2} \sigma(\varphi + \theta) \cos(2\varphi + \theta) d\varphi - 2bR \int_{\phi_1}^0 \sigma(\varphi + \theta) \cos(2\varphi - \theta) d\varphi \quad (6)$$

$$F_{N\tau}(\theta) = 2bR \int_0^{\phi_2} \tau(\varphi + \theta) \sin(2\varphi + \theta) d\varphi - 2bR \int_{\phi_1}^0 \tau(\varphi + \theta) \sin(2\varphi - \theta) d\varphi \quad (7)$$

$$F_{DP\sigma}(\theta) = -2bR \int_0^{\phi_2} \sigma(\varphi + \theta) \sin(2\varphi + \theta) d\varphi + 2bR \int_{\phi_1}^0 \sigma(\varphi + \theta) \sin(2\varphi - \theta) d\varphi \quad (8)$$

$$F_{DP\tau}(\theta) = -2bR \int_0^{\varphi_2} \tau(\varphi + \theta) \cos(2\varphi + \theta) d\varphi - 2bR \int_{\varphi_1}^0 \tau(\varphi + \theta) \cos(2\varphi - \theta) d\varphi \quad (9)$$

Here: $\sigma(\varphi + \theta)$ is the normal stress while C-leg rotation angle of the C-leg is θ and the deflection angle on the flange is φ . $\tau(\varphi + \theta)$ the shear stress on the above corresponding position. From Eq. (6) - Eq. (9), it can be seen that for the above formulas, the expression of normal $\sigma(\varphi + \theta)$ and shear stress $\tau(\varphi + \theta)$ on the wheel flange should be derived first.

2.4. The test process

The sand tank test was studied in this paper. The tested wheel was placed in the middle of the sand tank, and the rope is used to prevent platform from advancing. It is not allowed to affect the up-and-down movement of the test wheel. In the test, the weight of the three legs on one side and its bracket is shared by the tested wheel and the pin of center column. When the test wheel leaves the sand tank, the platform is balanced by wheel 1, wheel 2, and pin. While studying the relationship between the ground support force, drawbar pull of the C-leg and the normal force, shear force on the wheel flange, it is needed to make the tested wheel rotate at a certain speed, repeating 20 times. The test result is stored in the computer directly by the data acquisition system. The ultimate test data is from the average 20-time test results.

3. Results and analysis

3.1. The result of the experience

In tank test, the change law of the shear and normal stress in wheel flange with rotation angle θ can be tested. In the same time, the change law of the support ground and drawbar pull on the axle with rotation angle also can be obtained, as shown in Figure. 4. In Figure. 4(b), the ground support force and drawbar pull are measured by the three-dimensional force sensor on the C-leg shaft. GSFfit is a fitting curve of the ground support force, and DPfit is a fitting curve of drawbar pull.

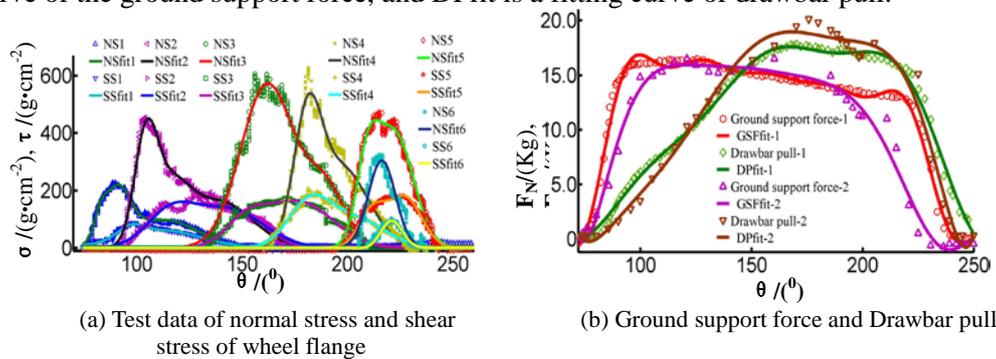


Figure.4 Test data of C-shaped leg wheel

3.2. Test data processing

3.2.1. Numeric insertion. It can be seen from the test data Figure. 5(a) that six sets of sensors are installed on the C-leg wheel, but in most cases the normal stress sensor (or shear stress sensor) has only 2 to 3 readings. It is clear that the measurement data is small if using it to analyze the stress of C-leg distribution rule. Therefore, numerical insertion method is used to insert some values between the sensors. The normal stress (or shear stress) on the wheel flange is continuously changed. The closer the point is to the sensor, the more similar normal stress (or shear stress) changes with the sensors. So the position weighted average numerical interpolation method used. On the basis of the measurement value, it will be inserted between the two sensors to make up for the data shortage. The detailed operation of numerical insertion in this paper is as follows: Firstly, aligning the data columns measured by the two sensors during the process of sand entry referring to the peak. Secondly, the

weight of the two sensor measurements in the insertion value is determined by the number of values to be inserted. Then the insertion value is obtained according to the weight of the average. The data column of the insertion value can be obtained by means of average of the one by one correspondence. Finally it will be inserted into the corresponding position. Whether the inserted value is accurate or not, the ground support force and the hook traction force obtained by the C-shaped leg and sand action can be directly measured by installing a three-dimensional force sensor on the C-shaped leg shaft, and the calculated values of the Eq. (4) and (5) can be obtained. In comparison, if the ground support force and hook traction force obtained by the two methods are the same, it indicates that the method of inserting values is feasible.

3.2.2 Sensor measurements and insertion values and regression equations. The normal stress and shear stress data columns can be obtained from measurement and inserted values. The curve fitting tool of MATLAB software (Curve Fitting Tool) can be used. The regression equations are obtained by Gaussian function fitting. They can be expressed as:

$$\sigma(\theta)_{jks} = \sum_{i=1}^n a_{jki} \exp(-((\theta - b_{jki}) / c_{jki})^2) \quad (10)$$

$$\tau(\theta)_{jks} = \sum_{i=1}^n u_{jki} \exp(-((\theta - v_{jki}) / w_{jki})^2) \quad (11)$$

Here, fitting parameters include a_{jki} , b_{jki} , c_{jki} , u_{jki} , v_{jki} and w_{jki} . j and k are the serial number of the sensor group, taking six numbers 1-6. s is the serial number of the inserted value. Figure 5 shows the fitting curve for the measurement and insertion values. Figure 5 (a) shows the 32 normal stress fitting curve. The red are the fitting curves of the normal stress measurement (Fitting curve of test values of normal stress), and the blue are the fitting curves of the normal stress insertion value (Fitting curve of inserted values of normal stress). Figure 5 (b) shows the 32 shear stress fitting curve. The red are the fitting curves of the shear stress measurement (Fitting curve of test values of shearing stress), and the blue curve is the fitting curve of the shear stress insertion value (Fitting curve of insert values of shearing stress).

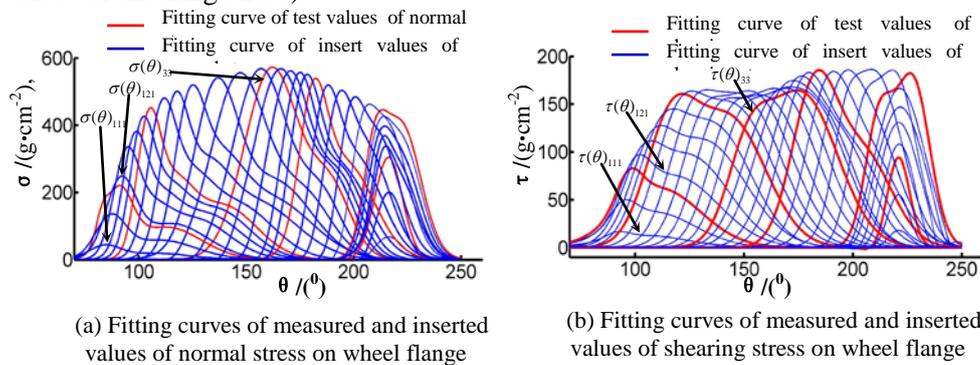


Figure.5 Fitting curves of measurement and insertion values on the C leg flange

3.2.3 The normal and shear stress on the flange and its regression equation While C-leg enters the sand and revolves to arbitrary angle θ , the shear and normal stress value of the sensors and insertion points on the flange would be derived by the above 64 regression equations. Then, it can be obtained through the means of curve fitting that the regression equations of shear stress $\sigma(\varphi + \theta)$ and normal stress $\tau(\varphi + \theta)$ in θ changed with φ . The equations are as follows

$$\sigma(\varphi + \theta) = \sum_{i=1}^n a_i \exp(-(((\varphi + \theta) - b_i) / c_i)^2) \quad (12)$$

$$\tau(\varphi + \theta) = \sum_{i=1}^n u_i \exp(-(((\varphi + \theta) - v_i) / w_i)^2) \quad (13)$$

Here: a_i , b_i , c_i , u_i , v_i and w_i are fitting parameters.

3.3. Results analysis

3.3.1. The ground support force and drawbar pull. The ground support force and drawbar pull can be obtained when the C-leg rotates to θ angle by substituting Eq. (12) and Eq. (13) into formula (4) to (9). In this paper, the values of the ground support force and drawbar pull can be calculated when θ angle is set in the range of 75° to 250° (C-leg enters into the sand at the angle of 78° and goes out the sand at the angle of 240°) at 5° intervals as shown in Figure.5(b). The regression equation of each fitted curve can be obtained by software MATLAB. This paper uses sine function fitting.

From the fitting parameters, the average value of the ground support force and the hook traction force calculated from the measured values of the rim normal stress and the shear stress sensor are calculated within the range of the C-leg sand entering angle. The average ground support force and hook traction force obtained were 14.21 Kg and 13.28 Kg, respectively.

Similarly, in the range of $\theta = 85^\circ$ to $\theta = 210^\circ$, the average values of the ground support force and the drawbar pull are calculated by three-dimension force sensor are respectively 14.91kg and 13.12kg.

3.3.2. Analysis of experimental results. Through Figure.5(b), there are the consistent changing rule of the ground support force and drawbar pull, which are measured directly by the three-dimensional force sensor on the C-leg's axle and calculated by the given integral model for the normal stress and the shear stress (measured and inserted value) on the wheel flange, respectively, as shown in Figure.5(b). Contrasting with the average value from $\theta = 85^\circ$ to $\theta = 210^\circ$, it can be seen that the relative error, $\gamma_{NSJ} = (\bar{F}_{NS} - \bar{F}_{NJ}) / \bar{F}_{NS}$ between \bar{F}_{NS} and \bar{F}_{NJ} , $\gamma_{DPSJ} = (\bar{F}_{DPS} - \bar{F}_{DPJ}) / \bar{F}_{DPS}$ between \bar{F}_{DPS} and \bar{F}_{DPJ} , are respectively 4.69% and 1.16%. In other word, the relative error are both less than 5%.

4. Conclusion

This paper addressed the integral model of the interaction of C-leg wheel and soil, studied numerical interpolation between stress sensors on the C-leg flange, proposed a "positional weighted average interpolation method", and given the concrete method to calculate the expression $\sigma(\varphi + \theta)$ of normal stress, and the expression of shear stress $\tau(\varphi + \theta)$ on the C-leg flange. The change rules of the ground support force and drawbar pull obtained by the integral model are consistent with that measured by three-dimensional force sensor. In the $\theta_1 = 85^\circ$ to $\theta_2 = 210^\circ$ range. The relative error of the ground support force and the drawbar pull calculated from the integral model and measured by the three-dimensional force sensor, respectively, is less than 5%. This shows that the integral model presented is correct, the proposed "positional weighted average interpolation method" is feasible. The research results could provide theoretical and technical support for establishing the mathematical model of wheel-soil interaction.

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