Dynamic modeling simulation and analysis of amplitude frequency characteristics on Tandem-Heavy oscillating rollers

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Abstract. Based on the oscillation compaction mechanism, the dynamic model of ‘roller-soil’ five degrees of freedom was established after the structure of the oscillation roller was simplified. The time-amplitude response characteristics of the oscillatory compaction system under pure rolling condition was analyzed by Matlab/Simulink simulation, and the amplitude-frequency characteristics of the oscillating wheel was analyzed by the design of related tests. The results show that the horizontal vibration of the frame and the above part of the oscillating roller can not be ignored in the practical work; Considering the horizontal vibration of the frame and above, the five degrees of freedom model can better respond to the actual working condition of the oscillating roller; the amplitude frequency characteristic curve provides the theoretical basis for the continuous adjustment and intellectualization of the working parameters of the oscillating roller.

1. Introduction
In order to study the dynamic process of oscillatory compaction of oscillatory roller and its amplitude-frequency response characteristics, it is necessary to establish a multi degree of freedom dynamic model similar to the actual situation\textsuperscript{[1]}. At present, there are three kinds of models of oscillatory compaction-soil system: single degree of freedom model, two degree of freedom phased model and four degree of freedom model. The dynamic response of oscillating roller can be qualitatively analyzed by single-degree-of-freedom model, but the horizontal displacement of oscillating roller was ignored, and the road slip problem of oscillating wheel and road surface was not considered. The two degree of freedom phased model considered the effect of slip on the interaction between the wheel and the ground, but at this present stage most of the oscillating rollers are double-wheel rollers\textsuperscript{[2-3]}, but the model does not take into account of the effect of another wheel vibration. The four-degree-of-freedom model was the system of the front and rear steel wheels simultaneous oscillation, the difference between it and the actual situation is that the vibration displacement in the horizontal direction of the frame can not be analyzed.

In this paper, the influence of the horizontal direction vibration of the frame and above on the oscillating amplitude was considered, and the dynamic model of ‘roller-soil’ five degrees of freedom was proposed and established. Through the simulation based on Simulink of Matlab, the dynamic process and response characteristics of oscillating roller compaction under pure rolling condition was analyzed\textsuperscript{[4]}, Then the accuracy of the model was verified by relevant experiments, and the amplitude
and frequency characteristics of the oscillation were verified and analyzed. The proposed model provides the basis for the prediction of compaction condition and the optimization of the roller’s working parameters.

2. The establishment of Five degrees of freedom dynamic model

Series double steel wheel oscillating roller produced periodic horizontal excitation force through eccentric block oscillation, which was applied to compacted soil. The soil was gradually compacted by providing horizontal friction adhesion to the oscillating wheel after being subjected to alternating shear force. Under certain conditions, the oscillating wheel is affected not only by the adhesion of the road surface and another steel wheel, but also by the horizontal vibration of the frame and the parts above it\(^5\)-\(^6\). Considering the above working characteristics and characteristics of the oscillatory roller, a dynamic model of ‘whole machine and soil’ with five degrees of freedom is established as shown in figure 1. The following assumptions are made for the dynamic model.

1. Assuming that the mass of each part of the roller is symmetrical and uniformly distributed along the longitudinal axis of the machine, the whole machine-soil system is simplified as a plane oscillation mode\(^7\)-\(^8\). It is considered that the mass of the vibratory roller frame and cab during compaction can be regarded as the central position of the roller and simplified as the mass block in the central position. 3. It is considered that the vibratory medium is connected with the stationary earth by elastic elements, and that only a small part of the medium is involved in the vibration, and the mass can be ignored. 4. At the present stage, the model only studies the pure rolling condition, does not consider the oscillatory roller slip, and the friction between the roller and the road surface compaction medium is the conditional coupling between the roller and the road surface compaction medium. 5. It is considered that the simplified mass block between the vibratory roller frame and the cab is supported by the stationary earth with zero friction coefficient. The five degrees of freedom dynamic model of series double-steel wheel oscillating roller was shown in Fig.1.

![Diagram](image_url)

Figure 1 The five degrees of freedom dynamic model of series double-steel wheel oscillating roller

According to the Lagrange equation of analytical mechanics\(^8\):

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_k} \right) - \frac{\partial T}{\partial q_k} + \frac{\partial U}{\partial q_k} + \frac{\partial D}{\partial \dot{q}_k} = Q_k \quad (k = 1, 2, 3 \ldots n) \tag{1}
\]

In the formula, T: the kinetic energy of the system; \(q_k\): the generalized coordinate system; U: the potential energy of the system; D: the energy consumed by the system; \(Q_k\): the generalized force of the system.

Available through computational collation, the kinetic equation ws as follows:

\[
m_1 \ddot{x}_{01} + k_2 (x_{01} - x_3) - k_1 (r \dot{\theta}_1 - x_{01} + \dot{x}_3) + c_2 (\ddot{x}_{01} - \dot{x}_3) - c_1 (r \dot{\theta}_1 - \ddot{x}_{01} + \dot{x}_3) = 0 \tag{2}
\]

\[
m_2 \ddot{x}_{02} + k_2 (x_{02} - x_3) - k_1 (r \dot{\theta}_2 - x_{02} - x_3) + c_2 (\ddot{x}_{02} + \dot{x}_3) - c_1 (r \dot{\theta}_2 - \ddot{x}_{02} + \ddot{x}_3) = 0 \tag{3}
\]

\[
m_3 \ddot{x}_3 - k_2 (x_{01} - x_3) + k_2 (x_{02} + x_3) + k_1 (r \dot{\theta}_1 - x_{01} + x_3) - k_1 (r \dot{\theta}_2 - x_{02} - x_3) = 0 \tag{4}
\]
\[ -c_2 (\ddot{x}_{01} - \ddot{x}_3) + c_2 (\ddot{x}_{02} + \ddot{x}_3) + c_1 (\ddot{r}_1 - \ddot{x}_{01} + \ddot{x}_3) - c_1 (\ddot{r}_2 - \ddot{x}_{02} - \ddot{x}_3) = 0 \]  \hfill (4)

\[ J_1 \ddot{\theta}_1 + k_r (r\theta_1 - x_{01} + x_3) + c_1 r (r\theta_1 - \dot{x}_{01} + \dot{x}_3) = M_s \sin \omega t \]  \hfill (5)

\[ J_2 \ddot{\theta}_2 + k_r (r\theta_2 - x_{02} - x_3) + c_2 r (r\theta_2 - \dot{x}_{02} - \dot{x}_3) = M_s \sin \omega t \]  \hfill (6)

The matrix form of formula 2, 3, 4, 5 and 6 was as follows:

\[ [M][\ddot{x}] + [C][\dot{x}] + [k][x] = [p] \]  \hfill (7)

In the formula, \([M]\) : the mass matrix; \([\ddot{x}]\) : the acceleration, velocity and displacement vector matrix; \([k]\) : the stiffness matrix; \([C]\) : the damping matrix; \([p]\) : the external force matrix.

In order to obtain the relationship between the input excitation torque and the swing amplitude of the front and rear wheels, the Laplace transformation of the 7 formula was carried out, and the following results was obtained:

\[ (M s^2 + C s + k) X_0 = k_i M \]  \hfill (8)

For the convenience of writing, the following assumptions was made by using the substitution method:

\[ A = m_1 s^2 + (c_1 + c_2) s + (k_1 + k_2) \]  \hfill (9)

\[ B = -(c_1 + c_2) s - (k_1 + k_2) \]  \hfill (10)

\[ C = -c_1 r s - k_r r \]  \hfill (11)

\[ D = m_2 s^2 + (c_1 + c_2) s + (k_1 + k_2) \]  \hfill (12)

\[ I = m_3 s^2 + 2(c_1 + c_2) s + 2(k_1 + k_2) \]  \hfill (13)

\[ N = J_1 s^2 + c_1 r^2 s + k_r r^2 \]  \hfill (14)

\[ R = J_2 s^2 + c_2 r^2 s + k_r r^2 \]  \hfill (15)

\[ F = C = K = L = P = Q = -J = -M \]  \hfill (16)

\[ E = -B = -G = H \]  \hfill (17)

3. Example simulation

For example, the 12t vibrating oscillatory roller developed by Luoyang Lutong Heavy industry machinery limited company. Known: \( m_1 = m_2 = 3400\text{kg} \), \( r = 0.7\text{m} \), \( J_1 = J_2 = 833.12\text{kg} \cdot \text{m}^2 \), \( m_3 = 5200\text{kg} \), \( M_1 = M_2 = 106400\text{N} \cdot \text{m} \), \( C_2 = 0.951 \times 10^4\text{N} \cdot \text{s} / \text{m} \), \( k_2 = 3.46 \times 10^6\text{N} / \text{m} \). Referring to the experimental results of the existing road roller\(^{[9]}\), choose: \( k_1 = 1.51 \times 10^7\text{N} / \text{m} \).
\[ C_1 = 3.71 \times 10^4 \text{N} \cdot \text{s} / \text{m} \].

3.1. The establishment of simulation model block diagram

Using Simulink simulation module in MATLAB to build a dynamic model simulation block diagram of the series oscillating rollers with five degrees of freedom, as shown in the diagram.

3.2. Analysis of simulation result

![Two-degree-of-freedom oscillation wheel swing time domain response diagram](image1)

![Five degrees of freedom rear swing amplitude time domain response map](image2)

Figure 3 Two-degree-of-freedom oscillation wheel swing time domain response diagram

Figure 4 Five degrees of freedom rear swing amplitude time domain response map

From the comparison between figure 3 and figure 4, it can be seen that the amplitude of oscillating wheel swing amplitude is a certain value when the exciting frequency is constant and the excitation torque changes according to the sinusoidal law in the "oscillatory wheel-soil" model with two degrees of freedom. In the five degrees of freedom 'oscillating wheel - soil' model, when the excitation frequency is constant, the exciting torque changes according to the law of sine. Due to the influence of the horizontal vibration of the frame and above, at the beginning of the initial vibration, the swing amplitude of the oscillating wheel first increases and then decreases. After a period of time, the swing amplitude of the oscillating wheel tends to be stable. Therefore, the five degrees of freedom model can better reflect the amplitude of the oscillating wheel.

![Time domain response diagram of horizontal displacement of the front wheel with five degrees of freedom](image3)

![Time Domain response Diagram of horizontal displacement in frame and above of five degrees of Freedom](image4)

Figure 5 Time domain response diagram of horizontal displacement of the front wheel with five degrees of freedom

Figure 6 Time Domain response Diagram of horizontal displacement in frame and above of five degrees of Freedom

From the comparison of figure 4 and figure 5, it can be seen that the rear wheel of the oscillating roller is the driving wheel, and the amplitude of the oscillation of the rear wheel during the initial oscillation is smaller than that of the front wheel. The amplitude of the horizontal displacement of the front wheel fluctuates greatly, and the horizontal amplitude of the front wheel tends to be fixed with the stabilization of the horizontal vibration of the frame and its parts. As can be seen from figure 6, the...
vibration amplitude of the frame and above is gradually increased to stabilized under the effect of rubber shock absorbers. Therefore, the vibration in the horizontal direction of the frame and above has a significant influence on the amplitude and frequency characteristics of the front and rear steel wheels, which cannot be ignored.

4. Experimental examples
In order to study the relationship between amplitude and excitation frequency of oscillating roller in the actual work, in the test center of Luotong heavy Industry Machinery Co., Ltd, two groups of in-situ oscillation tests of 12t oscillating roller were carried out: the front wheel was stationary, the rear wheel was oscillating and the front and rear wheels were oscillating at the same time.

4.1. Test content and methods
(1) The two sections of the pavement with the same compaction degree are selected for the use of the two groups of experiments;
(2) An acceleration sensor is installed at the center of the wheel on both sides of the rear steel wheel of the roller, and two acceleration sensors are installed at the position relative to 180 degrees along the wheel edge;
(3) During the test, the frequency of exciting vibration was taken at: 5 Hz, 9 Hz, 13 Hz, 17 Hz, 21 Hz, 25 Hz, 29 Hz, 33 Hz, 37 Hz, 41 Hz, 44 Hz, respectively, to conduct the test;
(4) Maintain the static rear wheel oscillation of the road roller in the first section of pavement, and carry out the test. The steel wheel oscillates at the same exciting frequency on the second stage pavement[10].

4.2. Analysis of test results:

Figure 7 shows that the amplitude and frequency characteristic of the oscillating wheel is worth comparing with that of the two-degree-of-freedom model under the condition that the front steel wheel is still and the rear steel wheel is oscillating. Figure 8 shows that the amplitude and frequency characteristics of the oscillating wheel are worth comparing with the model theory of five degrees of freedom under the condition of simultaneous oscillation of the front and rear steel wheels. The figure shows that, although the working state of the front steel wheel is different, the amplitude-frequency characteristics of the oscillating wheel have something in common: 1, when the excitation frequency of the oscillating wheel is small, the swing amplitude increases with the increase of frequency, and a larger value appears around 6Hz. After the frequency of oscillation increases, the amplitude of...
oscillation amplitude decreases gradually. After a minimum, it increases with the increase of frequency. When it reaches a certain maximum, it decreases slowly with the increase of frequency. 2. When the stiffness and damping of the soil are a definite value, the maximum amplitude of the frequency characteristics is around 35 Hz.

From the comparison between figure 7 and figure 8, it can be seen that, the swing amplitude of the oscillating wheel is small in frequency and small in variation, when the angular frequency is larger, due to the influence of the frame and above. The slope of the dynamic model of five degrees of freedom is much larger than that of the dynamic model of two degrees of freedom. The vibration mode of front wheel and rear wheel is often used in the actual compaction of double steel wheel oscillating roller. From the comparison of the experimental results, the five-degree-of-freedom dynamic model can better reflect the actual working condition of the oscillation wheel. At the same time, the amplitude-frequency characteristic curve of the oscillating wheel provides a theoretical basis for the continuous adjustment of the oscillating wheel swing amplitude and angular frequency, and also provides a theoretical basis for the intelligent control of the oscillating roller.

5. Conclusion
(1) A dynamic model of 'soil-whole machine' with five degrees of freedom is proposed, which can reflect the working characteristics of heavy series oscillating roller under pure rolling condition. The model is closer to the actual working condition of the oscillating wheel.

(2) The vibration in the horizontal direction of the frame and above of the oscillating roller has a great influence on the swing amplitude of the oscillating wheel, which can not be ignored.

(3) The experimental results show that the optimal exciting frequency of the oscillating wheel is about 35HZ, and the amplitude-frequency characteristic curve provides a theoretical basis for the continuous adjustment and intelligence of the operating parameters of the oscillating roller.

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