Research on the Method for Analyzing the Degree of Impact Acceleration and Compaction of the Impact Roller

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\textbf{ABSTRACT} For the construction process of striking and rolling to treat the foundation, the traditional compaction test must conduct core sampling and damage detection, which are time-consuming and strenuous. Furthermore, it is difficult to determine the actual overall compaction. Based on acceleration sensor and satellite positioning measurement technology, this paper designs and develops an acceleration information acquisition device for impact construction, which can auto monitor impact construction in large-scale pavement construction. This paper also proposes methods for analyzing the degree of impact acceleration and compaction, including: (1) comprehensive analysis of the functional requirements and structural levels of a device for the acquisition of information about impact acceleration; (2) development of an acquisition system for collecting information about impact acceleration installed on the roller; (3) proposal of a method for the processing and analysis of compaction information based on the collected acceleration information; and (4) proposal of an experimental scheme of to test impact acceleration and application of the whole set of developed equipment to practical engineering.

\textbf{INDEX TERMS} Compaction degree, construction quality, correlation analysis, feature extraction, impact.

\textbf{I. INTRODUCTION}

The foundation treatment \cite{1} is the most important basic link in all kinds of engineering construction. The quality of the foundation treatment directly affects the quality of engineering and even safety. Especially in airport construction, the process with the longest construction period and the largest amount of construction is the foundation construction. Compaction is one of the most important treatment processes in foundation construction. In the field of modern engineering construction, the bearing capacity and stability of the rock filler, soil and asphalt are closely related to the compaction degree of the materials. Effective compaction can significantly improve the bearing capacity and stability of the foundation pavement materials, reduce the water damage, and improve the pavement durability.

The impact roller, which was first used in South Africa, is a typical example of the application of tamping technology; in other words, by using the irregular polygonal impact wheels, it constantly strikes the ground as it travels forward \cite{2}, but due to its continuous movement and instantaneous strikes, the results of strikes and rolling is a kind of restriction on the construction supervision and project quality.

The traditional methods of measuring the compaction degree include the ring knife method and the core method, which require strict manual operation by professionals, and are destructive local tests with serious technical bottlenecks. Unlike this pit sampling test, the nuclear density meter can detect the soil water content and density by using radioactive elements; based on the law that different wavelengths correspond to different penetration depths \cite{3}, Rayleigh wave can detect the actual compaction condition without destroying the construction road surface. However, this kind of indirect measurement method is costly, requires strict test conditions, and cannot obtain comprehensive compaction information. In addition, for different soil quality, this method faces great limitations in the development of its application.
To compensate for the defects of these detection methods, the traditional engineering construction has been gradually transformed into digital construction, and an increasing number of high-performance road rollers have been successfully developed, such as the German oscillating roller and American double-steel tandem vibratory roller [4], [5]; the American Trimble Company is the first to introduce the GPS [6] technology to the construction monitoring field to detect the accurate rolling times. The Bomag Company of Germany has combined the GPS technology and long-distance communication technology before successfully developing the MSGPS (Measuring System Global Positioning System), which can accurately detect the position of the roller [7], [8] but does not reflect the real-time compaction of the impact construction. Indirect measurement methods, which are based on acceleration sensors [9], have not been popularized and are mostly applied to vibratory impact rollers. Especially due to the strong dynamic characteristics of the impact construction, the collected complex data are inevitably interrupted by substantial noise, which is challenging for the compaction analysis.

Therefore, on the premise of the full analysis of the impact construction process of airport construction, it is necessary to develop a device for the acquisition of information of impact acceleration that can be applied to the global compaction analysis of impact construction and to realize the automatic acquisition and unified preservation of the impact acceleration and GPS information. Combined with modern digital signal processing, important parameters, such as the traveling speed of the impact roller and the rolling times, are extracted for the compaction analysis of the road roller. Thus, real-time compaction quality can be determined [10], and timely rework can be conducted on the unsatisfactory sections to ensure the construction quality.

II. IMPACT COMPACTION PRINCIPLE

The impact roller uses a triangular or pentagonal-shaped “wheel” to produce concentrated impact energy to compact the earth and rock fillers. The impact compactor can be towed in front by a supporting heavy industrial trailer, or it can be equipped with its own tractor.

As shown in Fig. 1, the left and right width of the impact wheel of the impact roller is 0.9m, and the middle width is 1.0m. Upon return, one wheel is pressing in the middle space, and the other wheel is near the outer wheel track. Because the inner wheel presses on the ground that was last pressed, when the roller advances horizontally to the other side of the roadbed, it evenly compacts the ground twice. The usual construction principle is: the compacting first occurs on the roadside and subsequently in the middle of the wheel track staggered, so the whole surface of the roadbed is covered in one run.

The principle [11] of the impact compaction technology is to use an eccentricity dynamic load to instantly transform the potential energy into kinetic energy, so the soil vibrates and is compacted. With a greater potential energy, the depth of soil reinforcement is greater with the characteristics of high impact force and high efficiency. In the process of impact compaction, through the periodic transformation between potential energy and kinetic energy of the compaction wheel into concentrated impact energy acting on the ground, the purpose of continuous crushing and compacting pavement can be achieved, and broken fragments are directly pressed into the foundation. Thus, the work efficiency is improved, the construction time is shortened, and the project cost is reduced.

III. OVERALL DESIGN

A. QUALITY EVALUATION OF IMPACT COMPACTION

The on-site compaction quality is expressed by the compaction degree. For subgrade soil and pavement base, the compaction degree refers to the ratio of the actual dry density achieved at the construction site to the maximum density obtained from the indoor standard compaction test. Moreover, for asphalt pavement, the compaction degree refers to the ratio of the actual density achieved at the site to the standard indoor density.

The impact acceleration and rolling times of impact roller are essential parameters to reflect the compaction degree of subgrade. The impact acceleration information acquisition device installed on the impact roller can supervise the construction compaction quality by measuring the impact acceleration data and impact point position. At the same time, the monitoring of rolling times, thickness, and rolling speed can be realized by the GPS equipment on the device.

B. CORRELATION ANALYSIS

In general, the smaller the compactness of the subgrade, the higher the energy absorbed, and the smaller the acceleration response signal. On the contrary, the larger the compactness of the subgrade, the smaller the energy absorbed, and the higher the acceleration response signal. Therefore, there is a good correlation between the acceleration response signal and the compaction degree. Through the analysis and processing of the corresponding waveform of acceleration, the relationship between the compaction degree and the acceleration response signal can be easily obtained. It is feasible to use the characteristic value of acceleration to reflect the change of compaction degree.

Taking the rolling process of the trilateral impact wheel adopted in this project as an example, when the impact wheel rotates around point \(D\) under the traction force \(F\) (which can
be divided into horizontal force $F_2$ and vertical component force $F_1$) and falls under the action of gravity $G$, the moment of contact between the impact wheel and the ground is subject to the friction $f$, the supporting force $N$ at point $D$ and the reaction force $F'$ of impact force, as shown in Fig. 2. According to the mechanism analysis of the construction process of the fundamental impact rolling, the reaction force $F'$ which was received at the moment of contact between the impact wheel and the ground is the most important force of ground soil compaction, and it is also the most important feature that reflects the soil compaction.

![FIGURE 2. Force diagram of impact wheel.](image)

With the continuous increase in rolling times, the compactness of pavement continues to increase. The impacted soil is close to the elastic state gradually, and the reaction force from the pavement is constantly changing into the whole process of the impact wheel. Therefore, the compaction degree of construction can be judged by analyzing the impact acceleration. Through the direct measurement and data analysis of impact acceleration and rolling position, a suitable function expression reflecting the compaction degree can be established. In this way, the conversion to the compaction degree can be realized in order to make a scientific evaluation of the construction quality.

### C. COMPARISON WITH TRADITIONAL COMPACTION TEST

The compaction degree is one of the key indexes for the quality control of subgrade and pavement construction. The traditional detection methods of subgrade compactness, no matter the ring knife method, sand pouring method, or nuclear measurement method, are mainly relying on on-site “sampling”. All of them stay in the resulting test and need to drill and sample on the compacted road surface. These detection methods are inefficient, and they are difficult to fully reflect the overall compaction of the pavement. They are time-consuming and laborious, which can also destroy the compacted pavement structure layer.

At present, there have been some studies on the acceleration sensor installed on the vibratory roller, which have verified the correlation between vibration acceleration and compaction degree. According to the field test [12], [13], the relationship between the effective value of vibration acceleration and the compaction degree of subgrade was obtained. The results showed that there was a significant positive linear correlation between the effective value of vibration acceleration and the compaction degree of subgrade, which could accurately reflect the compaction degree soil. The correlation between compaction degree, rolling times, and effective value of vibration acceleration was also verified.

At present, the use of technologies such as acceleration sensors and GPS to monitor the compaction quality has been a trend in the construction of vibratory rollers, but the application researches on impact rollers are very few.

Based on the directly detected compaction degree, according to the research results at home and abroad, it is found that there is a certain correlation between acceleration-rolling times and compaction-rolling times, as shown in Fig. 3.

![FIGURE 3. Relationship diagram of impact acceleration-rolling times-compaction.](image)

Compared with the traditional construction methods, the method of characterizing the compaction quality studied in this paper has the advantages of real-time, non-destructive, comprehensive, and high efficiency, and it is a process monitoring method. This paper mainly designed and developed the testing device of impact rolling and compaction, including impact acceleration information acquisition device and GPS monitoring equipment. The theoretical analysis methods of impact acceleration and compaction degree were studied. The impact acceleration information acquisition device was installed on the impact roller and was applied to the actual construction to realize the dynamic monitoring of impact compaction quality. Due to the limited conditions, the traditional subgrade compaction test, such as the ring knife method, had not been carried out.

### D. SELECTION AND ANALYSIS OF ACCELERATION SENSOR

When the impact roller works, the environment is relatively inadequate. According to the actual investigation, the sensor is selected by comprehensively considering the parameters such as measuring range, quality, sensitivity, etc. In this paper, LC0107T built-in IC piezoelectric acceleration sensor with small size, lightweight, strong anti-impact ability and high reliability is selected. Its sensitivity is 100mV/g, and the range is $-50g \sim +50g$. The LC0107T acceleration sensor consists of a piezoelectric acceleration sensor and a miniature IC amplifier. The sensor comes with a constant current source.
module for generating an excitation voltage. The relevant technical parameters are shown in Table 1.

The selected acceleration sensor has the following indicators: (1) linearity: ≤ 1%; (2) transverse sensitivity: ≤ 5%, typical value: ≤ 3%; (3) output bias: 8-12VDC; (4) constant current: 2-20mA, typical value: 4mA; (5) output impedance: < 150Ω; (6) temperature range: −40 °C ∼ +120 °C; (7) discharge time constant: ≥ 0.2s; (8) shell insulation resistance: > 10^6Ω; and (9) installation torque: about 20kgf.Cm.

When measuring the impact acceleration, the rigid parts of the impact roller wheel and the piezoelectric acceleration base are fixed together. When the accelerometer is vibrated, the alternating charge will be generated on the two surfaces of the piezoelectric chip due to the piezoelectric effect, which is proportional to the acting force (specimen acceleration). Through this relation principle, the piezoelectric accelerometer can transform the vibration acceleration into electrical vibration measurement. The internal impedance of the piezoelectric sensor is high, and its output charge is usually small. Therefore, it is necessary to adjust and convert the signal when using, and usually connect its output to the preamplifier with high input impedance.

As shown in Fig. 4, the equivalent circuit diagram of the connection between the sensor and the charge amplifier is formed by connecting the sensor and the charge amplifier.

![FIGURE 4. Charge amplifier equivalent circuit.](image)

where \( q \) is the charge generated by the sensor, \( A \) is the open-loop amplification of the charge amplifier, \( R_o \) is the open-loop amplification of the charge amplifier, \( R_i \) is the input resistance of the sensor, \( R_i \) is the input resistance of the charge amplifier, \( C_a \) is the inherent capacitance of the sensor piezoelectric element, \( C_i \) is the equivalent capacitance of the input cable, \( C_i \) is the input capacitance of the amplifier, \( C_f \) is the feedback loop capacitance, \( U_i \) and \( U_o \) are the input and output voltages of the charge amplifier.

Therefore, the equivalent parallel capacitance is \((1+A)C_f\). Moreover, the parallel connection of charge source and capacitance can be equivalent to the series connection of voltage source and capacitance. The formula can be obtained:

\[
U_o = -U_i = -\frac{q}{C_a + C_c + C_i + (1 + A)C_f} \tag{1}
\]

Usually \( A = 10^4 \sim 10^6 \), so if \((1+A)C_f \gg C_a + C_c + C_i\), the formula (1) can be expressed as:

\[
U_o = -\frac{q}{C_f} = -(S_q/C_f)a \tag{2}
\]

where \( S_q \) represents the charge sensitivity of the sensor and \( a \) represents the acceleration detected by the sensor. According to formula (2), the output voltage is only related to \( q \) and \( C_f \). The time constant of the input loop is affected by \((1+A)C_f\). When it is very large, the influence of \( C_a, C_c \) and \( C_i \) can be ignored. The charge only charges the \( C_f \), and the voltage sensitivity of the sensor is almost not affected by the cable capacitance, so replacing the cable will not change the sensitivity of the sensor. Therefore, the charge amplifier can be regarded as a high-gain operational amplifier with negative feedback capacitance and high input impedance. It converts the high output impedance of the piezoelectric accelerometer into the low output impedance of the preamplifier and then matches the measuring instrument.

### E. OVERALL DESIGN AND IMPLEMENTATION OF ACQUISITION DEVICE

The development goal of the whole acceleration information acquisition device is to acquire the acceleration signal and GPS signal during the impact construction process and to store and manage all the collected data. This paper proposes a feasible acceleration information-processing algorithm, which adopts the idea of soft measurement, to study the relationship between acceleration and rolling times. The algorithm is used to detect and analyze the impact construction compaction. Data analysis mainly refers to the analysis methods that analyze the transient impact acceleration signals by digital signal processing [14]. The overall structure of the acquisition device is shown in Fig. 5, which includes
FIGURE 6. Overall implementation scheme.

FIGURE 7. Installation diagram of the acceleration sensor.

IV. DESIGN AND IMPLEMENTATION OF SOFTWARE AND HARDWARE

A. DESIGN AND IMPLEMENTATION OF HARDWARE

The overall scheme design of the acquisition of terminal hardware system includes the following main parts: the power conversion module, acceleration sensor, GPS device, data acquisition device, and computer.

Through the actual observation of the impact roller, there is a plane position between the tractor frame and the impact wheel bearing. It is a rigid connection, rising and falling with the impact wheel. Therefore, the middle position of this plane is selected as the installation position of the acceleration sensor, as shown in the black module of Fig. 7.

There are usually three ways to fix the acceleration sensor: screw, magnetic mount, and adhesive. The screw installation requires drilling holes in the traction frame, which can easily cause high-frequency parasitic vibration while damaging the construction machinery. On the other hand, a single magnetic base or adhesive cannot guarantee the strong vibration to withstand the impact. Therefore, this paper adopts the combination of magnetic seat and adhesive. Firstly, the installation position is polished with sandpaper to make the surface smooth. Secondly, the sensor is fixed on the hexagonal mounting seat. Finally, it is placed on the magnetic seat, and glue is evenly smeared between the hexagonal mounting seat and the magnetic seat, meanwhile between the magnetic seat and the construction machinery. The physical installation diagram of the acceleration sensor of the impact roller can be seen from Fig. 8.

The system works in the following steps: during the impact construction process, the acceleration sensor detects and
acquires the impact acceleration signal in real time, which is obtained by the USB capture card [17]. Then, the signal experiences the analog-to-digital conversion and data buffering and is uploaded to the computer via the USB bus. A GPS device is used to obtain the current construction position information of the roller and interact with the computer through serial communication. Finally, the upper computer software saves and displays the collected data. This hardware system adopts a box-mounted structure, which makes the whole machine firm, sealed, and durable and can effectively improve its ability to resist impact.

B. DESIGN AND IMPLEMENTATION OF SOFTWARE

The overall structure of the acquisition system software includes three major modules, namely, the display layer, control layer and data layer, whose purposes are to implement functions, such as device detection, parameter setting, data acquisition, display and storage, and data playback.

Auto start can be available for the software under the control of the hardware power switches. The system will successfully detect the acquisition device and configure the parameters before it enters the main interface of the automatic acquisition.

To acquire the impact acceleration, the sampling frequency [18] is set to 1 kHz, and three subthreads for data acquisition, storage and display are created. After the acquisition card initialization completes, the main thread will activate the HS3 acquisition thread using a timer, and the display thread and data storage thread are initially in a sleep state. The acquisition thread collects data of a certain depth of storage before the data display thread and data storage thread are activated by the timer.

To acquire the GPS data, serial communication is conducted. This process is designed to acquire the position information every 1 s. The entire collected GPS information is completed in one thread. To avoid mistaking that the device as being able to collect data due to the failure of start, the software prepares 5 opportunities to start the GPS. The timer queue calls the GPS acquisition function (AT command) after the function is successfully started to collect, analyze, display and save the GPS information.

V. DATA PROCESSING AND ANALYSIS

In the actual construction process, due to the complicated structure of the compacted soil, which contains gas, water and irregular crushed stones, even if the impact roller punches the ground in a split second every time, complex fluctuations are caused by the acceleration [19]. Using the soft-measurement idea, this paper builds the equation of the acceleration-rolling time function by directly measuring and analyzing the impact acceleration and rolling position. By analyzing the relationship between the impact acceleration and rolling times, the best number of rollings for the compaction effect is determined, which realizes the conversion of the compaction degree.

A. DATA PROCESSING

1) DATA ASSOCIATION

The number of rolling times is an important indicator of construction quality monitoring and is the key to obtain compaction. Since the impact acceleration data and GPS data acquired by the acquisition system are independent of each other, based on the two data, it is necessary to determine the actual rolling times and provide data support for the model construction. Based on the principle of certain interpolation, the GPS data are aligned with the acceleration data before correlating them. The linear interpolation method is used by this paper to supplement the GPS data. Then, the acceleration data are matched with the acquisition time according to when the file is started, and Fs/1000 ms is the incremental time difference. Finally, for any given GPS position, the point is taken as the position center, a certain area is extracted, and the acquisition time is determined by the file operation before the corresponding acceleration data are searched for according to the timeline. Then, the impact acceleration of the position is obtained.

2) DATA NOISE REDUCTION

Due to the complexity of the dynamic acceleration signal during the punching process, the monitored raw acceleration data are interfered. Thus, there is serious interference to the essential characteristics of the signals, which are not conducive to further data processing and analysis. Therefore, noise reduction should be applied to the original acceleration data obtained by data association to improve the data availability, and that process is the key to the subsequent feature extraction and calculation.

Compared with the limitation by the fixed short-time Fourier transform function window [20], the wavelet transform [21], [22] can form a series of time windows with different resolutions by expanding and translating the mother wavelet, which obtains the local time-frequency information of the signal using different scale signals. Therefore, the wavelet transform can be considered different forms of the local features of the time domain under different scaled signals. When the original signal and noise signal show distinct discrete characteristics in the spectrum, the signal can be denoised. For the low-frequency characteristics of the impact acceleration, the signal is successfully reconstructed using the MATLAB wavelet analysis toolbox, three layers of decomposing the original signal by the db1 wavelet, analysis of the default parameters by the default threshold [23]–[25], and inverse wavelet by the processed parameters. The noise reduction algorithm is shown in Fig. 9.

![Diagram of the data-denoising algorithm.](image-url)
3) FEATURE EXTRACTION

When the impact roller is working, the acceleration of the impact wheel at the moment of striking the ground is the actual compaction degree of the roadbed, while the acceleration information acquisition system acquires the continuous time signals. Hence, the effective acceleration data are only shown at the peak of the signal pulse, and the research on the peak extraction method of acceleration signals is of great significance to analyze the compaction degree. Because the impact wheel strikes multiple times during a certain time period, this paper proposes a partial envelope peak detection method to calculate the rolling speed on that basis. According to the above discussion, the design flow of the partial envelope peak detection method is shown in Fig. 10.

![Flow chart of the impact acceleration detection algorithm.](image)

The method mainly includes four aspects: First, based on wavelet denoising, we apply envelope smoothing to the acceleration data, which are shown as the searching of the maximum acceleration signal in a given data interval (10 data per set). Three-spline interpolation is conducted among the maxima to solve the envelope of the signal. Then, the largest envelope signal is extracted by the peak extraction method of acceleration signals is of great significance to analyze the compaction degree. Because the impact wheel strikes multiple times during a certain time period, this paper proposes a partial envelope peak detection method to calculate the rolling speed on that basis. According to the above discussion, the design flow of the partial envelope peak detection method is shown in Fig. 10.

\[ L = \frac{2\pi R \cdot F_s}{3v} \quad (3) \]

where \( R \) is the radius of the impact wheel, \( F_s \) is the sampling frequency of the acceleration information acquisition system, and \( v \) is the driving speed. Then, \( L \) is the data length between two adjacent impacts, so \( \Delta N \) should be within \((L, 2L)\).

According to the actual investigation, the radius of the impact wheel of the roller is 8-12km/h, and the sampling frequency of our system is 1kHz. Therefore, to adapt to any working condition and take as many effective acceleration values as possible, \( \Delta N \) should be within \((943, 1256)\), and this paper sets \( \Delta N = 1000 \).

4) RELATIONSHIP FITTING

To further analyze the relationship between the impact acceleration and rolling times, the acceleration data are processed under different rolling times with the traditional fitting method. In the data processing, the least squares method [26] can hold the overall trend of the signal and extract the trend component of the signal. Therefore, the least square method is selected to fit the effective impact acceleration under different rolling times at the same position.

The least squares method is used to make the fourth-order fitting for the peak of the impact acceleration to obtain a smooth fitting curve of the characteristic parameters of the compaction degree \( l(t) \), i.e.,

\[ l(t) = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3 + \beta_4 t^4 \quad (4) \]

where \( \beta = [\beta_0 \beta_1 \beta_2 \beta_3 \beta_4]^T \) is the coefficient vector, which is calculated by Formula (4):

\[ \beta = \left( H^T H \right)^{-1} H^T y \quad (5) \]

where \( y = [\text{peak}_1 \text{peak}_2 \ldots \text{peak}_m]^T \) is the peak value of the acceleration after the \( i \)th impact on the position by the roller, and \( l(t = 1, 2, \ldots, m) \) is the rolling time. The extracted acceleration feature data are fitted by the acceleration-rolling relationship, and a trend that reflects the changed acceleration information (which can reflect the changed compaction degree) can be obtained from the fitting curve.

B. DATA ANALYSIS

1) SUMMARY OF THE LAW

Based on the above acceleration data-processing process, this paper intends to select different data from multiple different sets of positions under identical construction conditions and obtains the initial inherent law between the acceleration and rolling times, which can be used as the premise of the compaction degree obtained from the acceleration-rolling function.

2) STATISTICAL CORRELATION ANALYSIS

The least square fitting of the acceleration-rolling times is performed for the data at different positions, and multiple sets of fitting curve equations with the identical structure and different parameters can be obtained. Then, from the perspective of correlation, the relationship among multiple sets of fitting curves is analyzed. If the curves are strongly correlated with one another, then the extracted data can well represent the actual construction situation, and we should select the common component from it because the effective impact acceleration varies with the rolling times under the regional working condition.

3) FUNCTION DETERMINATION

Based on the correlation analysis [27] results, the common components are extracted from multiple sets of
acceleration-rolling time fitting relation equations, and the effective parameters of the equation are determined to find a more applicable acceleration-rolling time function relation equation.

For the expressions with the identical structure and different parameters, the first step is to conduct a statistic analysis on the parameter distribution. Then, we set the expression of the solution as \[ y = \hat{a} + bt + \hat{c}t^2 + \hat{d}t^3 + \hat{e}t^4 \] following the principle of function error minimization. Finally, we obtain \( N \) groups of fitting curve expressions of \( y_i = a_i + b_it + c_i t^2 + d_it^3 + e_it^4, i = 1, 2, \ldots, N \). The objective function is:

\[
    \text{obj} : \min \left( \sum_{i=1}^{N} |\hat{y} - y_i| \right) \tag{6}
\]

that is:

\[
    \text{obj} : S = \min \left( \sum_{i=1}^{N} (\hat{y} - y_i)^2 \right) \tag{7}
\]

where \( S \) is the objective function. To solve equation (7), we must only solve the first-order partial derivative of \( S \) to \( \hat{a}, \hat{b}, \hat{c}, \hat{d}, \hat{e} \) to obtain the regional functional relationship equation of the acceleration-rolling times.

4) RELATIONSHIP VERIFICATION

The field test data are used to verify and optimize the function relation equation to improve its reliability and validity.

VI. EXPERIMENTAL VERIFICATION AND ANALYSIS OF RESULTS

A. EXPERIMENTAL VERIFICATION

In the practical engineering application, the environment of impact rolling construction is complex and diverse. There are a variety of factors that affect the stable operation of the system, such as extreme weather, high vibration, etc. These factors will affect the reliability and operating life of the system. Through the research on the design of the acquisition system and the compactness analysis scheme, this paper integrated the development of the acceleration information acquisition device. In order to verify the working performance of the developed device in the actual construction environment, the experimental test and result analysis were carried out in the impact rolling construction site of Chengdu Tianfu International Airport. Due to the limitation of experimental conditions and time, only the construction of the same soil was tested and analyzed, and the practical application effect and test results of the device were analyzed in detail.

The sampling rate of HS 3 acquisition card was set to 1 kHz with a range of 8V and a storage depth of 10K; the GPS acquisition frequency was 1Hz; and the data retention period was 15 min.

The acceleration sensor was installed at the rigid structure of the impact wheel of the impact roller, and the specific installation position can be seen from Fig. 7 and Fig. 8. The GPS antenna was fixed on the roof of the cab and sealed against rain. The acquisition terminal equipment based on virtual instrument technology integrated data acquisition equipment, computer, power conversion module, GPS host, etc., and realized the functions of data acquisition and processing, data storage and distribution. The acquisition terminal equipment was placed in the cab, and the box structure was adopted. Moreover, the protective box was solid, sealed and durable as a whole, and can effectively improve the impact resistance of the device. The side of it was the device-related interface, which connects the acceleration sensor and the extended GPS antenna with the SIM808 module. The acceleration sensor interface was BNC(Bayonet Nut Connector), and the GPS interface was screw-fastened. Finally, the relevant cables were connected to the device box and fixed accordingly. The physical diagram of the device is shown in Fig. 11.

B. ANALYSIS OF CASE EXPERIMENT RESULTS

To fully verify the law of acceleration-rolling times, based on the associated data, 15 data points were extracted from the rolling positions for analysis. To avoid the effect of the moving speed of the roller, we should avoid all positions of the turning points. The rolling positions were marked as \( p_1, p_2 \ldots p_{14} \) and \( p_{15} \). Taking the first pass of \( p_1 \) and \( p_2 \) as an example, the actual waveform and spectrum of the acceleration data are shown in Fig. 12.

1) DATA NOISE REDUCTION

Fig. 12 shows that the measured acceleration contains obvious global oscillation noise and variable frequency components with very complicated characteristics of the time domain and frequency domain. According to the principle of wavelet denoising, the extracted data are denoised, and the energy ratio is taken as an important parameter to weigh the...
noise reduction effect. Energy ratio $P$ is the energy loss before and after signal denoising in the calculation formula:

$$P = \frac{E_0}{E_i} = \frac{\sum_{n=1}^{N} |x_0(n)|^2}{\sum_{n=1}^{N} |x_i(n)|^2}$$

(8)

where $E_0$ is the energy of the signal noise reduction process; $E_i$ is the energy of the original signal; and $N$ is the data length.

Similarly, the measured acceleration data of Fig. 12 are taken as an example. Fig. 13 shows the noise reduction results. The trend of the acceleration data is displayed, with all energy ratios above 84%, which indicates that the noise reduction process retains the energy of the original signals up to the hilt while filtering out the noise. Thus, the noise reduction function of the impact acceleration data is realized, which provides technical support to further study the characteristics of the acceleration data.

![Waveform and spectrum of the first rolling original acceleration data.](image)

**FIGURE 12.** Waveform and spectrum of the first rolling original acceleration data.

2) FEATURE EXTRACTION AND RELATIONSHIP FITTING

Furthermore, according to the segmented envelope peak detection method, which selected the peak value of the noise-reduced data, we set the search length $N = 1000$ and made $N/5 = 200$ for the overlap region. The extracted peak values were important characteristic parameters that demonstrated the degree of construction compaction. Taking the data of a certain position as an example, if we obtained 5 peak values, then the time interval of the impact points was $T = 4000/5000 = 0.8s$. We could estimate that the horizontal moving speed of the roller was $v = 2\pi R/3T \approx 9.42$ km/h.

Based on this method, the data acceleration peak extraction result from 12 rolling times at a certain position obtained by data correlation is shown in Fig. 14.

Based on the aforementioned peak searches, the peaks of the impact acceleration at different positions were obtained before the fourth-order least square fitting was performed on the acceleration-rolling times at different positions. Thus, we obtained the corresponding fitting curve equation at 15 positions.

3) DETERMINING FUNCTION RELATIONSHIP

To better compare them, Fig. 15(a) puts the acceleration-rolling times changing trend fitting curve at any four positions at the same coordinate. The rollers have very similar fitting results of acceleration-rolling time relationship, i.e., both show the form of “slowly increasing–rapidly increasing–leveling off”. Therefore, we conducted a correlation analysis of the 15 fitting relation equation parameters. The results are shown in Fig. 15(b), where the dark colors correspond to a strong correlation, and the light colors correspond to a weaker correlation. Thus, we learn that the fitting equations of these 15 positions are quite similar to one another.

![Acceleration data denoising results of the first rolling at different positions.](image)

**FIGURE 13.** Acceleration data denoising results of the first rolling at different positions.

The obtained fitting equation coefficient is statistically analyzed, and its histogram is shown in Fig. 16, where the abscissa denotes the value interval, the ordinate denotes the corresponding frequency, and $a$, $b$, $c$, $d$, and $e$ denote the 4th-, 3rd-, 2nd-, 1st-powers and constant coefficient, respectively.

The coefficients obey the normal distribution, which indicates that the acceleration-rolling times in this region basically change in the same manner, so there is a certain inherent law among them.
To further analyze the fitting equation coefficients, such as the 4th power coefficient $a$ based on the drawn histogram, a single sample K-S test is conducted with the test results in Fig. 17.

The results show that the K-S test has the Z value of 1.176, and $P$ (sig 2-tailed) = 0.126 > 0.05, so the data are approximately in the form of a normal distribution.

In addition, the Q-Q figure test is performed. As shown in Fig. 18 QQ Plot, each point is approximately near a straight line, which indicates that the data are approximately in the form of a normal distribution.

Therefore, the distribution of coefficient $a$ is in the form of a normal distribution:

$$f(x) = \frac{1}{\sqrt{2\pi} \times 0.01653} \exp\left(-\frac{(x + 0.0135)^2}{2 \times 0.01653^2}\right)$$  (9)

Similarly, we analyze $b$, the 3rd power coefficient, $c$, the 2nd power coefficient and $d$, the 1st power coefficient,
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FIGURE 17. K-S test.

FIGURE 18. Q-Q figure test.

before obtaining the similar results. As shown in the above analysis, the coefficients of the equations “acceleration-rolling times” are in the form of a normal distribution, which indicates that there is indeed an inherent law between the regional acceleration-rolling times, and the rolling position selected within the experimental region is representative to some extent. The next step, based on their commonality, is to obtain the only equation, which should be always available under this working condition and demonstrates the acceleration-rolling times. On the premise of the statistical characteristics of normal distribution and the principle of minimizing the function error, we calculate the values and obtain:

\[ y = -0.0072x^4 + 0.1758x^3 - 1.3805x^2 + 5.4342x + 1.0341 \]  

where \( y \) is the value of the peak of the impact acceleration that can reflect the construction compaction degree, and \( x \) is the impact rolling times.

To further evaluate the functional relationship, the mean absolute error (MAE) that corresponds to the 15 locations is separately calculated. The MAE is used to characterize the deviation of the fitting result from the actual values. A smaller MAE implies that the functional equation can make more accurate estimation of the acceleration of the current rolling times. The MAE is obtained from equation (11):

\[ MAE = \frac{1}{N} \sum_{n=1}^{N} |y_i(n) - y_o(n)| \]  

where \( y_i(n) \) is the acceleration of different rolling times obtained from the original data feature extraction, \( y_o(n) \) is the result of equation (10), and \( N \) is the rolling time. The evaluation indicators are shown in Table 2.

| Location | MAE  |
|----------|------|
| P1-5     | 0.23 |
| P6-10    | 0.04 |
| P11-15   | 0.02 |

TABLE 2. Results of the mean absolute error at different locations.

The acceleration data processing method in the paper can build the function relationship of the acceleration-rolling times in a certain specific region and provide theoretical and technical support to analyze the degree of construction compaction.

VII. ANALYSIS OF DISADVANTAGES AND LIMITATIONS

The working environment of the acceleration information acquisition system is relatively complicated, and the selection of the acceleration sensor must meet the performance requirements such as range, accuracy, sensitivity, etc. The components, power supply, wiring, and other factors of the hardware circuit will produce noise to the circuit. If the noise is not suppressed pertinently, the further amplified noise will seriously interfere with the effective acceleration signal under the action of the signal conditioner. Based on the requirements of subsequent compaction analysis, all the collected data must be saved, which puts forward strict requirements for data acquisition rate and data storage equipment. The impact roller is moving all the time, and the installation of the sensor should follow the principles of reasonable structure, convenient installation, easy disassembly, and debugging. Considering the influence of the harsh construction environment in the field, the main structure of the hardware is required to be reliable and stable, which can ensure reliable data acquisition under various conditions, with strong environmental adaptability and portability.

At the same time, most of the impact constructions are in the wild mountains, where the subgrade soil is diverse, and the soil composition (dry humidity and irregular broken stone distribution) is very complex. Moreover, the impact roller construction itself has strong vibration, so that the acquisition system is inevitably subject to a variety of interferences, resulting in complex time-domain characteristics of impact acceleration. Therefore, the original data of impact acceleration obtained by the acquisition system cannot be used directly, and it needs to be filtered and preprocessed through data association and data noise reduction.

Due to the limitation of experimental conditions and time, this paper only tested and analyzed the construction of...
the same soil. In the next step, the extracted acceleration characteristic data will be fitted by the relationship between acceleration and rolling times for the soil quality of different regions. It can provide theoretical and technical support for the analysis of construction compaction degree, and realize the rapid and non-destructive evaluation of land compaction degree. Therefore, there are limitations on the initial expansion of the application.

VIII. CONCLUSION
The compaction degree is a key indicator in roadbed processing, and it is important and meaningful for construction quality supervision to carry out nondestructive testing. However, there are few studies on the construction of the impact rollers for airport construction. Based on the global studies of ground treatment, this paper adopts the idea of soft measurement and proposes a scheme to detect the compaction degree of construction based on the acceleration analysis. Through the direct measurement and data analysis of the impact acceleration and rolling position, the functional equation of acceleration-rolling times is established. An acceleration information acquisition device suitable for impact construction is developed, and a field experiment is carried out on the actual site to collect a large amount of data. By processing and analyzing the collected data and fitting the relationship equation, the compaction analysis method proposed in this paper is verified, which provides technical support to detect the compaction degree of the impact construction. The specific studies and results of this paper are as follows:

1. The overall development plan of the acceleration information acquisition device is proposed. The functions and performance requirements of the acquisition device are analyzed in a targeted manner. Finally, the overall implementation scheme is designed for the acquisition device, including the acceleration information acquisition system and acceleration information data analysis.

2. The acceleration information acquisition system is designed. The acceleration data and GPS data are simultaneously acquired, and the debugging of the entire data acquisition system is completed, which helped the system adapt to the particularity of the construction environment.

3. The analysis scheme of acceleration information data is designed. The collected data are analyzed and processed from four aspects: data association, data noise reduction, feature extraction, and relationship fitting. Based on the analysis of a large quantity of data, the rules are summarized. The method based on the similarity for the uniqueness induction is discussed. Finally, the automatic processing and analysis software for acceleration information data is developed.

4. The development results of the acceleration information acquisition device had been applied with the actual engineering signals analyzed and processed. Using the automatic data processing and analysis software, the relationship between the acceleration and the rolling times in the airport construction is analyzed, which verifies the effectiveness and practicability of the acquisition device developed by this paper.

The next work is to be carried out from the following aspects:

1. Furthermore, the field experiments of impact rolling will be carried out under different working conditions. The influence law between characteristic parameters (acceleration) and compaction degree in the different geological environments will be studied.

2. The selection of characteristic quantities reflecting the compaction degree will be further studied. The project selected the most intuitive and simple time-domain characteristic peaks. In addition, the research on harmonic ratio, impact energy, and CMV (Compaction Meter Value) is worth further discussion.

3. The intelligent compaction system of impact roller will be further improved and developed.

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