

## Research Article

### Research and Design on Detection System of Soil Compaction Degree Based on ARM

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**Abstract:** This study proposes detection methods of vehicular soil compaction degree based on a series of ideal conditions and GIS, which is to reflect the soil compaction degree and soil moisture through measuring the variation of acceleration amplitude of vibrating compaction wheels, in combination with the mathematical model of “vibrating drum-soil” two-degree-of-freedom vibrating system based on the analysis of the operating principle of vehicle; designs an embedded system based on ARM and modules such as the collection, processing and transmission of acceleration signals; writes application programs of system software in  $\mu\text{C}/\text{OS-II}$  environment; and develops a new detector of soil compaction degree. Experimental results show that this detection system can meet the requirement of comprehensive real-time monitoring for the soil compaction degree and soil moisture.

**Keywords:** Acceleration sensor, ARM, excitation signal, soil compaction degree, vibration test

## INTRODUCTION

Research of nutrients balance in farmland can help looking into the variety and problem possibly appeared in process of farmland nutrients degenerate and regenerate from macro angle (Zadeh, 1965). Over the years, experts and scholars at home and abroad have done a lot of research on the subject of the soil compaction degree and soil moisture. The European Environment Agency advisory panel defines soil compaction degree as: the soil density and disperse coefficient increased and porosity decreased by large load, vibration and pressure (Saeys *et al.*, 2004). The soil compaction not only changes the soil properties, but also affects the growth of crops (Craul, 1994). Therefore, the research for all the factors affected soil becomes meaningful (Mizumoto, 1995), (Fig. 1). Currently, the methods for detecting the soil compaction degree on site include sand cone method, nuclear gauge method and core cutter method. Sand cone method is to replace the volume of the test hole with uniform particles of sand, which can be used to test the density of various soils or pavement materials (Zhu *et al.*, 1997). Its disadvantage is that a large amount of sand should be carried, along with many times of weighing and a slow test speed. Nuclear gauge method is to measure the density and moisture content of soils or pavement materials by using radioactive elements, characterized by a fast measuring speed and a few personnel required, applicable to measuring the density and moisture content of various soils or pavement materials (Potts, 1994). Its disadvantage is that radioactive substances are harmful for human body and thus it is required to

perforate. The structure near the cave walls might be damaged in the process of perforation; therefore, the accuracy of measurement will be affected. In core cutter method, the volume of the cutting ring is often  $200\text{cm}^3$  and its height is about 5cm. The density measured by core cutter method is the average density within the depth range of the soil sample within the cutting ring. Though core cutter method is one allowed to be used in the specification, the mass of its sample is too small, affecting the accuracy and stability of test values to a certain extent.

This study proposes detection methods of vehicular soil compaction degree, which is to reflect the soil compaction degree and soil moisture through measuring the variation of acceleration amplitude of vibrating compaction wheels, in combination with the mathematical model of “vibrating drum-soil” two-degree-of-freedom vibrating system based on the principle of vibrating compaction and acceleration detection, develops a new detector for detecting the compaction degree, through which the construction department can detect the value of compaction degree online and in real time, thus saving the detection time, reducing the input of human and material resources.

## BASIC PRINCIPLES OF VEHICULAR SOIL COMPACTION DEGREE DETECTION

Vehicular soil compaction degree detection is to reflect the compaction condition of compacting materials based on the close relationship between the variation of dynamical parameters of vibrating drum and the compaction degree of compacting materials in the

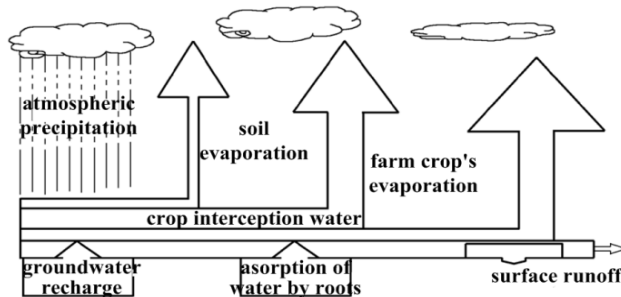


Fig. 1: The schematic diagram of the impact and change on soil compaction degree and soil moisture

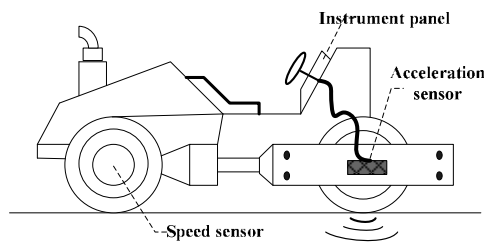


Fig. 2: Overall schematic diagram of vehicular soil compaction degree detection system

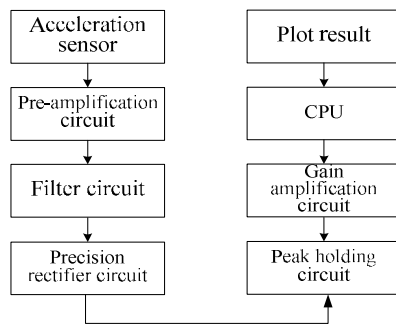


Fig. 3: Structure chart of the detection system

roller-soil model, especially the relationship between the shock excitation signal produced by the vibration exciter materials to be compacted. In the compaction work, the shock excitation signal is collected by the precise transducer installed on the vibrating drum and analyzed and processed by the processor and then the real-time value of compaction degree is obtained. The selection and confirmation of signal reflection method of compaction degree value is the key for studying compaction degree detector. Figure 2 shows the overall schematic diagram of the system.

**Structure of detection system:** In the process of vibrating compaction by the vehicle, the shock excitation signal is collected by the compaction degree measuring instrument through the acceleration transducer installed on the vibrating drum of vehicle and amplified by the amplifying circuit. Then, the weak

charge signal of the transducer is transformed into a useful voltage signal, which is filtered by the filter to remove the noise signal in the acceleration signal. Thus, the required voltage signal is obtained. A/D conversion device transforms the voltage signal collected into a digital signal which will then be stored in the microprocessor, processes the original signal and finally outputs the compaction degree value on the displayer. Figure 3 shows the overall structure of the detection system.

**Analysis on shock excitation signal of vehicle:** In engineering practice, after filling, a smooth-wheel roller is often used to roll the soil for twice and then a vehicle is used for repeated impact compaction. If the compaction degree of soil is expressed as  $E$ ,  $E$  and vibration parameters and working parameters of the vehicle have the following functional relationship:

$$E = f_1(P_L) + f_2\left(\frac{A\omega}{v}\right) \quad (1)$$

where,

$PL$  : The linear load of vibrating drum of the vehicle, N/cm

$A$  : The working amplitude of the vehicle, mm

$\Omega$  : The working frequency of the vehicle, rad/s

$v$  : The working speed of the vehicle, m/s

In order to overcome the cohesion and adsorptive power between soil particles, the vehicle must have a heavy enough linear load  $PL$  and large enough amplitude  $A$ . During the normal vibrating compaction, the vibrating drum always contact with soils and the amplitude of the vibrating drum reflects the deformation and pressure of soils. The higher the dynamic pressure is, the higher the shear stress bore by soils and the compaction degree of soils will be. It is thus clear that the amplitude of the vibrating drum indirectly reflects the compaction condition.

**Mathematical model of vibrating drum-soil:** In order to make the mathematical model of the vehicle matched with the actual working condition as far as possible, the

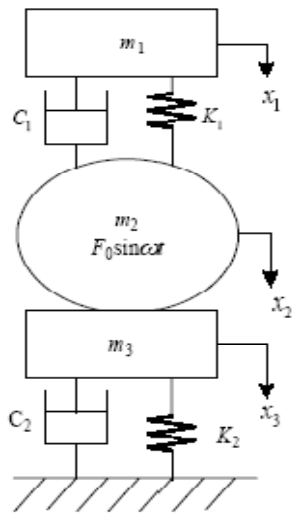


Fig. 4: Mathematical model of vibrating drum-soil system

mathematical model should be simplified, thus to provide a simple and practicable mathematical calculation method.

Assume that the soils to be compacted have an elastomeric with a certain stiffness  $k_2$  and a linear damping  $c_2$ ; the masses of the rack and vibrating drum of the vehicle are simplified to a lumped mass block with a certain mass,  $m_1$  for the rack and  $m_2$  for the vibrating drum; and the vibrating drum always keeps close contact with the ground at any time when the vehicle is working.

Figure 4 shows the mathematical model of “vibrating drum-soil” system after simplifications above.

where,  $x_1$  is instantaneous displacement of the rack (instantaneous amplitude);  $x_2$  is instantaneous displacement of the vibrating drum (instantaneous amplitude);  $m_1$  is the mass of the rack;  $m_2$  is the mass of the vibrating drum;  $k_1$  is the stiffness of the damper;  $k_2$  is the stiffness of soil;  $c_1$  is the damping of the damper;  $c_2$  is the damping of soil;  $F_0$  is excitation force;  $\omega$  is working frequency (angular frequency).

**Equation of motion of vibrating drum-soil system:** According to the vibration model, the equation of motion of the mathematical model in Fig. 3 is:

$$M\ddot{X} + C\dot{X} + KX = F \quad (2)$$

where,

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \quad C = \begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1 + c_2 \end{bmatrix}$$

$$K = \begin{bmatrix} k_1 & -k_2 \\ -k_1 & k_1 + k_2 \end{bmatrix} \quad F = \begin{bmatrix} 0 \\ F_0 \sin \omega t \end{bmatrix} \quad F_0 = M_e \omega^2$$

$M_e =$  The static centrifugal moment of the eccentric block:

$$M = J\ddot{\theta} + F_0 R, \quad M_e = m_f r$$

$m_f =$  Eccentric force and  $r$  is eccentricity of the eccentric block.

For a linear time-invariant system, when the shock excitation is resonance force, the result of differential Eq. (2) is:

$$x_1 = F_0 \left[ \frac{(A_1^2 + B_1^2)}{(C^2 + D^2)} \right]^{\frac{1}{2}} \quad x_2 = F_0 \left[ \frac{(A_2^2 + B_2^2)}{(C^2 + D^2)} \right]^{\frac{1}{2}} \quad (3)$$

where,

$$A_1 = k_1, \quad B_1 = c_1 \omega = B_2, \quad A_2 = k_1 - m_1 \omega^2$$

$$C = m_2 m_1 \omega^4 - m_2 k_1 \omega^2 - m_1 k_2 \omega^2 - c_1 c_2 \omega^2 + k_1 k_2 - m_1 k_1 \omega^2$$

$$D = k_2 c_1 \omega + k_1 c_2 \omega - m_2 c_1 \omega^3 - m_1 c_2 \omega^3 - m_1 c_1 \omega^3$$

The first-order and second-order natural frequencies (angular frequency)  $\omega_1$  and  $\omega_2$  of the vibrating system without damped mode are respectively:

$$\omega_1 = \left\{ \left[ \frac{(m_2 k_1 + m_1 k_2 + m_1 k_1)}{-\sqrt{(m_2 k_1 + m_1 k_2 + m_1 k_1)^2 - 4(m_1 m_2 (k_1 k_2))}} \right] / 2m_1 m_2 \right\}^{\frac{1}{2}}$$

$$\omega_2 = \left\{ \left[ \frac{(m_2 k_1 + m_1 k_2 + m_1 k_1)}{+\sqrt{(m_2 k_1 + m_1 k_2 + m_1 k_1)^2 - 4(m_1 m_2 (k_1 k_2))}} \right] / 2m_1 m_2 \right\}^{\frac{1}{2}}$$

As the acceleration  $a_2 = \omega^2 x_2$ , the amplitude of acceleration is:

$$a_{2,A} = \omega^2 F_0 \left[ \frac{(A_2^2 + B_2^2)}{(C^2 + D^2)} \right]^{\frac{1}{2}} \quad (4)$$

According to Eq. (4), the variation trend of compaction degree with  $K_2$  and  $C_2$  can be obtained by numerical method.

First other parameter values except  $K_2$  are given and a series of values in the order of smallest to largest are given to  $K_2$ , thus the variation trend of acceleration amplitude increasing with  $K_2$  can be obtained. The variation trend of acceleration amplitude with  $C_2$  can be calculated by using the same method. Figure 5 shows the calculation results.

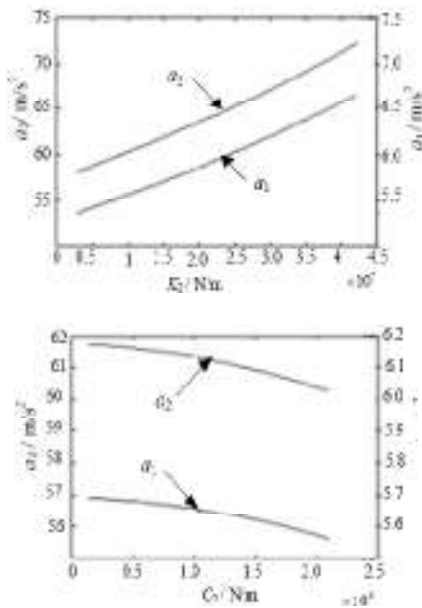


Fig. 5: Variation trend of acceleration with  $K_2$  and  $C_2$

In the actual process of compaction, the stiffness  $K_2$  of soil will increase and the damping  $C_2$  of soil will decrease along with the compaction. With the increase of soil stiffness and decrease of soil damping, the acceleration amplitude of compaction wheels will increase. That is to say, the acceleration amplitude will increase along with the compaction work.

### HARDWARE DESIGN OF VEHICULAR SOIL COMPACTION DEGREE DETECTION SYSTEM

**Overall design of hardware system:** Figure 6 shows the overall block diagram of hardware system of the vehicular soil compaction degree meter, which is mainly composed of transducer circuit, signal processing circuit and ARM microcontroller interface circuit.

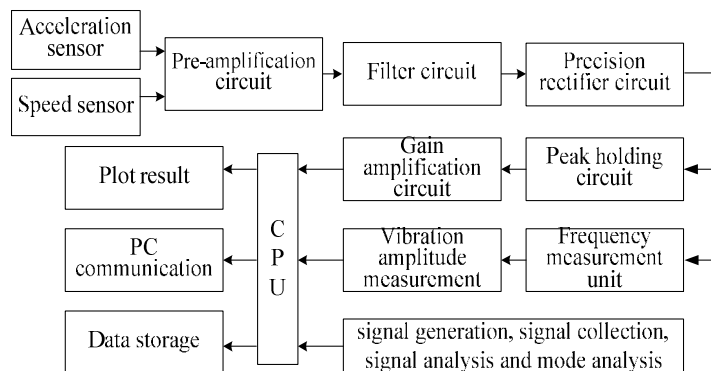


Fig. 6: Schematic diagram of the system

**Transducer module:** ADXL150 acceleration transducer of American AD Company is adopted. ADXL150 is a complete acceleration measuring system, the measuring range of which is  $\pm 50$  g. When supplied by 5V power, its sensitivity is 35 mv/g. The vibration amplitude of vehicle is  $\pm 4\sim 7$  g when compacting the pavement and is  $\pm 5\sim 10$  g when compacting the soil. If we consider with the maximum value 10 g, the voltage variation range of acceleration transducer is 350 mV. This value is relatively small. Therefore, gain amplification is necessary for the transducer signal. Figure 7 shows the amplifying circuit. C3 capacitance in the figure is 0.022UF, for the purpose of eliminating the effect of gravitational acceleration on the instrument. Resistance R2 is 300K $\Omega$  and the gain amplification factor is 3.3. The voltage variation range at OUTPUT end is 1.7V. The calculation formula of output voltage of the acceleration transducer is:

$$V_{out} = V_s / 2 - (Sensitivity \times V_s / 5 \times a) \quad (5)$$

where,

- $V_{out}$  : The output voltage of acceleration transducer,
- $V_s$  : The input voltage of the power
- $a$  : Acceleration.

**Precise full-wave rectification module:** Sinusoidal periodic signals from the band-pass filter will no longer present the original sinusoidal law with the gradually increasing compaction degree of soil. The shock excitation signal will produce distortion, which will become more obvious with the increasing times of compaction. Then the signal in the second half period will be transformed into a positive signal by the precise full-wave rectification circuit (Fig. 9). Therefore, the precise full-wave circuit composed of operational amplifier is selected and used, as shown in Fig. 8.

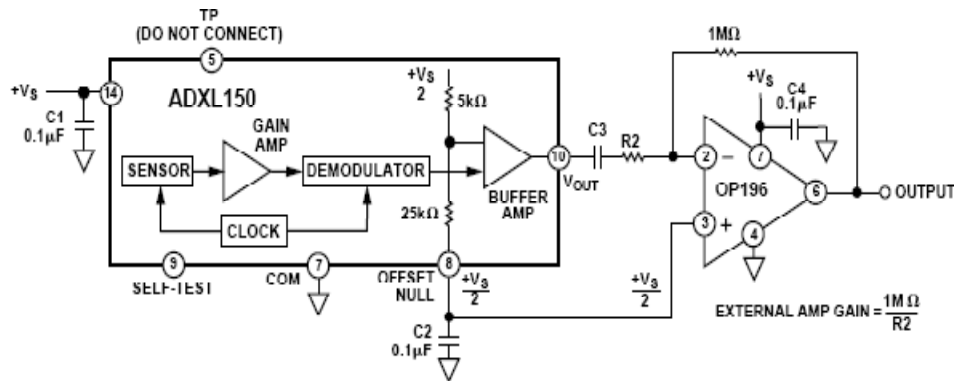


Fig. 7: Circuit diagram of transducer module

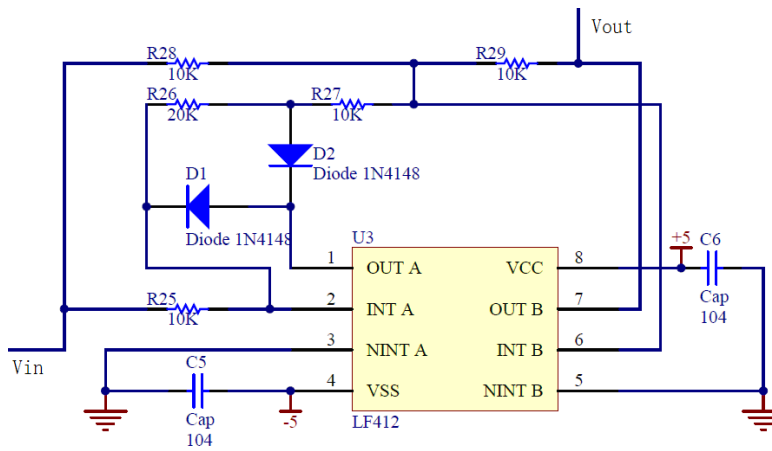


Fig. 8: Precise full-wave rectification circuit

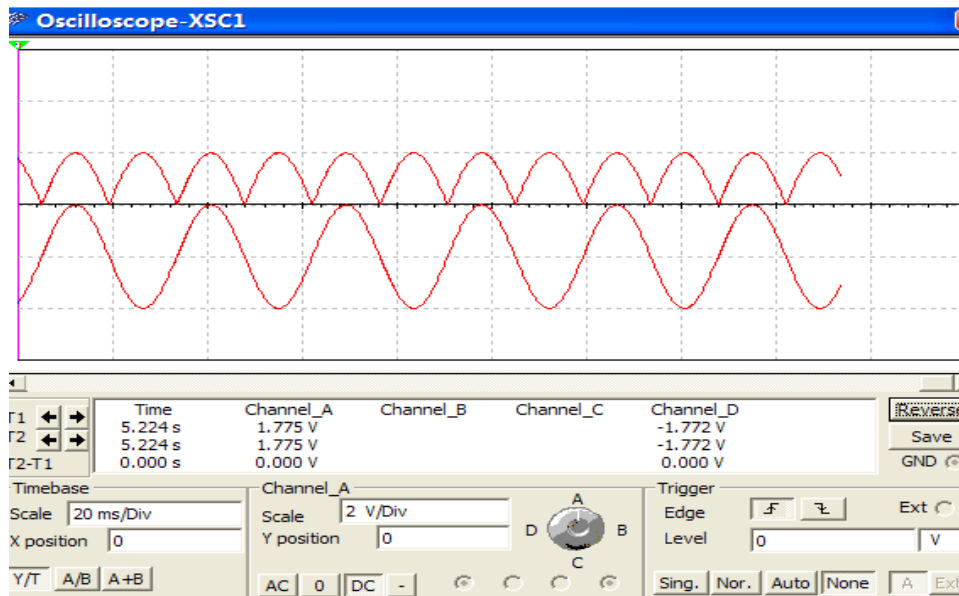


Fig. 9: Simulation waveform diagram of precise full-wave rectification circuit

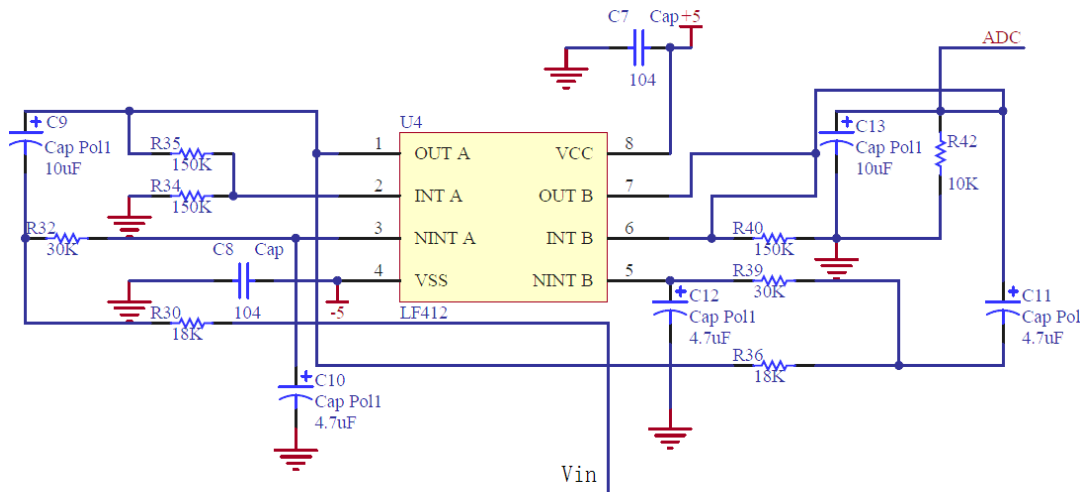


Fig. 10: Peak holding circuit

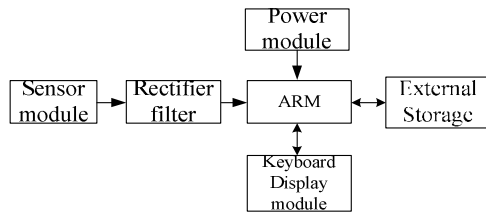


Fig. 11: Block diagram of ARM master control circuit system

**Peak holding circuit module:** The output of peak holding circuit can track and maintain the peak of input signal till the reset signal comes, or after the input signal terminates, discharge gradually through the discharge resistance.

With the gradually increasing compaction degree of soil, the shock excitation signal will produce distortion and the amplitude of the signal in the first half period will become sharper and narrower because peak signal seems as sharp pulse, which is very difficult for computer sampling. In order to detect the maximum amplitude of the signal accurately, we adopt a peak holding circuit module and extend the transient time of the peak signal. Figure 10 shows the specific circuit.

**ARM interface circuit design:** ARM microcontroller uses LPC213X series of Philip Company as the master control chip, which is a 32-bit microprocessor using ARM7TDMI-S kernel and characterized by high performance and low power consumption. It is mainly in charge of data processing and access in the overall system and communication with the outside world through the serial port so as to realize mutual data transfer. Figure 11 shows the block diagram of the master control circuit system.

## SOFTWARE DESIGN OF VEHICULAR SOIL COMPACTION DEGREE DETECTION SYSTEM

**Algorithm design of dynamic continuous detection module:** When the vehicle is rolling the loose elastic soil surface, the vibration acceleration signal presents a regular sine wave state. With the increasing times of rolling, such indicators of the soil as the compaction degree and bearing capacity will increase correspondingly, the pavement will gradually become hard and the acceleration of vibrating roller will produce distortion and upper harmonics. Components of the fundamental wave and secondary harmonic or above are compared and values of both are calculated so as to find its relationship with dynamic deformation modulus value (Evd).

The computer should conduct spectrum analysis on acceleration signals collected during data processing so as to obtain the amplitude distribution of each frequency component in the dynamic signal. The principle of spectrum analysis is based on Fourier transform principle, i.e., a complicated periodic vibration waveform can be disintegrated into the sum of sinusoidal and cosine signals of many different frequencies. When the vehicle is conducting vibrating rolling work, the acceleration transducer installed on the vibrating roller of the roller will continuously detect the vibrating signal of the vibrating roller. Then, the compaction degree detector collects and amplifies the vibrating signal and analyzes its amplitude and frequency. The computer calculates the corresponding modulus value according to the established mathematical model and then display or print and store the testing result.

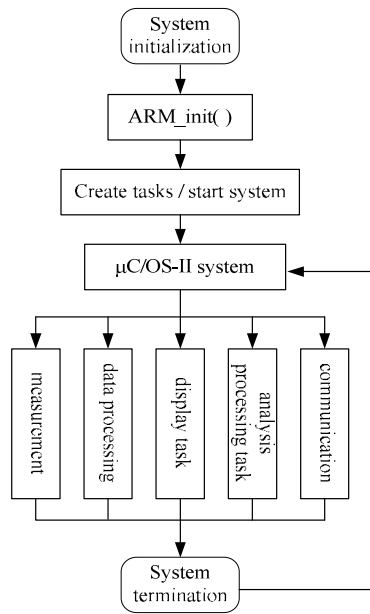


Fig. 12: Flow chart of system software

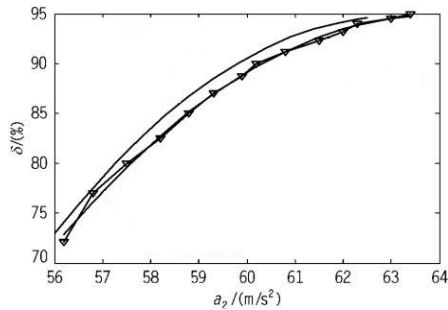


Fig. 13: Corresponding relation curve of acceleration  $a_2$  and compaction degree  $\delta$

The basic core of the algorithm of dynamic continuous detection is spectrum analysis on signals within the time domain, which is based on Fourier transform principle. Since the system has a strong real-time characteristic, fast Fourier transform is adopted in algorithm. The essence of FFT is to appropriately disintegrate DFT calculation with a long sequence into one with a short sequence.

**Software design of controller based on  $\mu\text{C}/\text{OS-II}$ :**

The selection of an embedded operating system mainly considers whether the operating system selected supports the hardware platform used and its transferability, the supporting degree of development tools, use-cost and the requirement of design for the performance of the operating system (such as the real-time characteristic and reliability).

LPC213X series microcontroller chip selected in this design doesn't have a memory management unit. In order to save I/O resources and reduce the cost, it is expected to download the operating system and all application programs to FLASH in the chip for operation. Therefore,  $\mu\text{C}/\text{OS-II}$  operating system is finally selected and used.

Software programs of the vehicular compaction degree detection system mainly include the task program, driver and compaction degree and amplitude measuring program, extremum removal average filtering method program, linear processing and task alarm processing program, code system conversion and display program and communication module programming.

In this system, first call OSInit() and initialize all variables and data structures of  $\mu\text{C}/\text{OS-II}$ ; then call arm-init() and initialize such hardware as the timer and serial port of the microcontroller; create each task in proper sequence by calling OSTaskCreate(); finally call OSStart() start-up system and start multitasking schedule. Figure 12 shows the control program module and process of the overall system.

**EXPERIMENTAL RESULTS AND ANALYSIS**

The 9013 piezoelectric type acceleration transducer is selected to detect the vertical acceleration of the vibrating drum according to the working environment of vehicle. The acceleration signal is input in the computer for processing, display and printout after amplified by BC-1 charge and transformed by AD536.

Detect the acceleration signal using the compaction degree detection system, measure the stiffness and damping of soil using the stiffness and damping detecting instrument, measure the compaction degree  $\delta$  with sand cone method and obtain the theoretical acceleration value  $a_2$  of vibrating drum; respectively draw the curves of actually measured  $a_2$ - $\delta$  and theoretically calculated  $a_2$ - $\delta$ , as shown in Fig. 13. The compaction degree of soil in the test section has been detected by two methods and each measuring point position corresponds.

From the comparative analysis of actual measurement curve and theoretical calculation curve of compaction degree in Fig. 13, it can be indirectly judged that the soil has a good compaction effect by using this detection system to detect the vibration acceleration of vibrating drum and the maximum error between the theoretical value and actually measured value is less than 2%.

This study respectively analyzes and studies the principles of the vibrating drum of vehicle-soil system and the vibrating compaction detection system and develops and designs a vehicular compaction degree detection system based on ARM on this basis, which

can measure the compaction degree of soil and the vibration frequency and amplitude of vehicle.

It is proved that this compaction degree detection system can realize real-time and continuous detection of the soil compaction degree of vehicle and can meet the requirement of agriculture application since the maximum error between the theoretical value and actually measured value is less than 2%.

#### **ACKNOWLEDGMENT**

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