Modeling of dynamic system "vibratory plate - soil" as an object quality control of compaction

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Abstract. In this paper, we consider an approach to modeling the process of vibrating plate interaction with soil, taking into account the elements of the method of continuous non-destructive testing of the quality of compaction. For a theoretical description of a dynamic system model, the state space method is used. A mathematical model is obtained on the example of a three-mass stacker vibration plate system. A simulation model of the process under study is constructed in the language of the MATLAB/Simulink program. The results of a computer experiment are presented.

1. Introduction

Improving the efficiency of stackers with vibrating plates is possible due to the intellectualization and digitalization of control and process control. This work is devoted to the stage of research work (R&D) on the topic "Intellectualization of control and management of technological processes and machines in capital construction". The problem of mathematical description of the control (management) object that implements technological processes in capital construction based on the methods of mathematical and computer modeling is solved.

From publications [1], [2], we know use of vibration plates on stackers as sealing aggregates. The technology of building coatings at a speed of up to 20 m/min has become widespread in the United States. The use of working bodies of stackers with tamper bars at high speeds of laying and compaction of the mixture is impossible due to the vertical cyclic vibrations of the bars (pressing bars) creating resistance to the movement of the machine. In this work, we solve the problem of a theoretical description by the method of space of states of the process of compaction of a mixture by a vibrating stacker plate. The construction of the model by the state space method provides a clear formalization and automation of calculation procedures [3].

The use of a vibrating plate improves the structure of the road surface and increases the degree of compaction. Compaction of the mixture is performed with constant contact of the vibrating plate with the mixture.

The main parameters of the dynamic system “vibration plate - soil” are frequency, amplitude, speed, acceleration. The amplitude of vibrations of the sealant depends on the physicomechanical characteristics of the material and changes during its deformation. Therefore, the proposed values of the oscillation amplitudes in the technical characteristics of the sealing machines should be adjusted taking into account the rheological properties of the material being compacted.
Improving the efficiency of the process under consideration is possible due to the use of the method of continuous non-destructive testing of the quality of compaction (continuous composite control, CCC) [4], [5]. Methods of spot non-destructive testing of seal quality are characterized by low productivity and increased danger to the operator due to the constant movement of machines during construction.

To implement the method of controlling the quality of compaction, data on the accelerations of the vibrating plate are necessary, the analysis of which allows to predict the degree of compaction [6].

2. The dynamic model in the state space

When developing a mathematical model of the compaction process, the following assumptions are made:

- the structural elements of the machine have absolute rigidity;
- the compacting vibrating unit of the stacker operates in shock-free mode with harmonic oscillations;
- the elastic-viscous properties of the shock absorbers are linear;
- the inertial properties of the medium to be sealed are taken into account.

The dynamic model of the interaction of the vibrating plate with the mixture is presented in figure 1. The obtained model allows us to determine the amplitude of plate vibrations and the dynamic parameters of medium compaction.

![Figure 1. Model of the dynamic system “vibration plate - soil”.

We used the following notations in figure 1: \( m_p \) – vibration plate weight, kg; \( m_f \) – frame weight, kg; \( F_e \) – exciter driving force, H; \( m_s \) – mass of compacted soil under the slab, kg; \( k_s \) – coefficient of elastic resistance of the soil under the plate, H/m; \( c_s \) – soil damping coefficient under the slab, H c/m; \( k_f \) – coefficient of elastic resistance of shock absorbers, H/m; \( c_f \) – shock absorber damping coefficient, H c/m; \( z_s, z_p, z_f \) – movement of the elements of the working body, respectively.

The influence of the mass of the attached soil on the dynamic system was studied in detail by Van Susante Paul J. and Michael A. Mooney [7]. Based on experimental studies and numerical modeling of the amplitudes of the vibrational displacement of the drum, the authors substantiated the mass of soil equal to 20% of the mass of the roller [7]. These data were used in this study.
The mathematical model of the compacted medium is represented by the elastic-viscous rheological model of the Kelvin-Voigt. A mathematical model has been compiled that reflects both the dynamics of vibrations of structural elements and the rheological properties of the medium being compacted. The system of differential equations describing the movement of the elements of the dynamic system “vibration plate - soil”.

\[
\begin{align*}
\left[ (m_s + m_p) \cdot \ddot{z}_p + c_s \cdot \dot{z}_p + k_s \cdot z_p + c_f \cdot \left( \ddot{z}_p - \ddot{z}_f \right) + k_f \cdot (z_p - z_f) \right] &= \\
= (m_s + m_p) \cdot g + m_e \cdot r_e \cdot \omega_e^2 \cdot \sin(\omega_e \cdot t) \\
m_f \cdot \ddot{z}_f - c_f \cdot \left( \ddot{z}_p - \ddot{z}_f \right) - k_f \cdot (z_p - z_f) &= m_f \cdot g; \\
\ddot{z}_p &= \ddot{z}_s; \\
z_p &= z_s,
\end{align*}
\]

(1)

where \( m_e \) – unbalanced shaft mass, kg; \( r_e \) – unbalance shaft eccentric radius, m; \( \omega_e \) – angular speed of the unbalanced shaft of the vibrator, Rad/s; \( \omega_e = 2 \cdot \pi \cdot f_e \); \( f_e \) – unbalanced shaft oscillation frequency, Hz; \( t \) – time, s.

Initial conditions: \( e = 0 \), \( \ddot{z}_p = \ddot{z}_s = 0 \), \( z_p = z_s = 0 \).

The state space method allows you to represent the control system in the form of a system of equations [3], [4], [5], [6], [7], [8]:

\[
\dot{x}(t) = A(t) \cdot x(t) + B(t) \cdot u(t);
\]

\[
y(t) = C(t) \cdot x(t) + D(t) \cdot u(t),
\]

where \( x(t) \) – state vector whose components are state variables of the \( n \)-th order system; \( y(t) \) – output vector the components of which are the output variables of the system; \( A(t) \) – system coefficient matrix \((n \times n)\); \( B(t) \) – input matrix \((r \times n)\), \( r \) – number of impacts; \( u(t) \) – input vector the components of which are input system variables; \( C(t) \) – output matrix \((n \times p)\), \( p \) – number of output quantities; \( D(t) \) – bypass matrix that determines the direct dependence of the output on the input.

Given the accepted notation, the state variables of a dynamic system are defined as follows: \( x_1 \) – vertical movement of the plate, \( x_2 = z_p \); \( x_3 \) – plate vertical speed, \( x_2 = \dot{z}_p \); \( x_3 \) – vertical movement of the frame, \( x_3 = z_f \); \( x_4 \) – frame vertical speed, \( x_4 = \dot{z}_f \).

The system of equations (1) in the normal Cauchy form, taking into account the accepted state parameters, will take the following form

\[
\begin{align*}
\dot{x}_1 &= x_2; \\
\dot{x}_2 &= \frac{1}{m_s + m_p} \cdot \left[ -c_s \cdot x_2 - k_s \cdot x_1 - c_f \cdot (x_2 - x_4) - k_f \cdot (x_1 - x_3) + \\
&\quad + (m_s + m_p) \cdot g + m_e \cdot r_e \cdot \omega_e^2 \cdot \sin(\omega_e \cdot t) \right]; \\
\dot{x}_3 &= x_4; \\
\dot{x}_4 &= \frac{1}{m_f} \cdot \left( c_f \cdot (x_2 - x_4) + k_f \cdot (x_1 - x_3) + m_f \cdot g \right).
\end{align*}
\]

(2)

Based on the system of equations (2), the following parts of the model are obtained in the state space.
3. The study of the mathematical model

To assess the adequacy of the mathematical model, numerical modeling was performed using the MATLAB/Simulink program.

To simulate the process we used the initial data from [9]

\[
\begin{align*}
 k_s &= 60 \text{ MN/m};
 k_f &= 3.2 \text{ MN/m};
 c_s &= 2026 \text{ kN/m};
 c_f &= 96 \text{ kN/m};
 m_p &+ m_s = 32 \text{ kg};
 m_f &= 16000 \text{ kg};
 m_r &= 32000 \text{ kg};
 \omega_e &= 2 \cdot \pi \cdot f_e \text{ rad/s};
 f_e &= 27 \text{ Гц}.
\end{align*}
\]

As a result of computer simulation, the dynamic parameters of the process of compaction of the soil by the vibrating working body of the stacker obtained the acceleration of the frame and plate (figure 3); contact force of the plate (figure 4).
The simulation results showed a good process adequacy in terms of the functional dependences of the displacement, speed, acceleration of the plate and frame, the contact force of the plate, taking into account the mass of the medium being sealed.

4. Conclusions
A mathematical model of the vibrational process of compaction of the mixture by the working body of the paver in the state space is obtained. The simulation model allows us to study the influence of variable factors of the "vibration plate - soil" system on the movement, speed, acceleration of structural elements, contact force of the plate during compaction. Vibration plate acceleration data can be used to analyze compaction ability with continuous compaction monitoring.

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