On the task of designing an object of cyber-physical quality control system for asphalt mixtures compaction

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Abstract. The results of formulation of computer model of highly-efficient constant non-destructive testing of quality compaction by state method have been considered. Computer model has regard to structural components of work tool and sealing material. The model of the sealing material is represented by a visco-elastic Kelvin-Voigt body. Result parameters are meant to analyse process dynamics, determine compaction quality continually, automate operation and control. A simulation model of the considered process was obtained in the language of the MATLAB/Simulink. Results of simulation of numerical example were provided.

1. Introduction
Strict requirements to the sealing of bituminous concrete surfaces provide a background for the implementation of digitization and intellectualization in the road construction industry.

The principal stages of the course of construction of the asphalt carpet are manufacture, transportation from the plant to the object, distribution, laying and sealing of the mixture affect the quality indicators of the coating [1]. Mix sealing with pavers and road pave train largely eliminates up to 50% of the disadvantages of bituminous surfacing and increases their service life [2].

Modern methods of sealing control of covering of roadway during construction are continuous non-destructive control systems of road surface sealing, which are installed on vibration pave train and which implement intelligent construction, intelligent sealing, and continuous sealing control technologies [3, 4, 5].

Pave trains with high-performance work tool can perform mix sealing to standard parameters. Depending on the achieved sealing coefficient, we can reduce the number of pave train behind paver, which would help increase the productivity of road construction, reducing the cost of coating. It is impossible to exclude the use of road pave train with existing technologies, since they are needed to fix the achieved sealing coefficient of the bitumen-concrete mix and increase the structural strength of the bituminous concrete. Considering the technology options of modern pavers to increase the efficiency and productivity of the sealing process in covering of roadway, it is necessary to provide continuous sealing control and regulation of operating modes by frequency compacting, frequency of pulsed movements of the pressing planks. Currently, there are no such automatic control and management systems for pavers. In the presence of such process automation systems, it is possible to design a "smart" paver with a significant reduction in the workload of the driver.

The paper considers theoretical description of a cyber-physical road construction system object, it’s a pave train with a performance work tool. Theoretical studies of various road-building sealing materials are considered and conducted by many Russian [6, et al.] and foreign scientists [7, 8, et al.]. The disadvantages of the existing computer models of the studied processes are computational difficulties in...
the design of control systems, the study of dynamic systems that the object under consideration belongs to.

To eliminate these shortcomings and improve the efficiency of theoretical research of the control object using modern MATLAB software, it is recommended to use the state space method, which allows for clear formalization and automation of computational procedures [9-11].

2. Mathematical formulation of the problem
The high-efficiency work tool was adopted for research in the following composition of sealing units "ramming board – plate – two pressure bars". The process of mix compacting is performed with a constant contact of the vibration plate with the mixture. The mix sealing is characterized by deformation of the mixture with a ramming board and a kinematic drive (the main sealing for 4-6 actions), a finishing plate and pressure bars. The plate improves the covering of roadway structure and fixes the achieved degree of coating sealing. Pressure bars create periodic pulse loading with a frequency of 50-70 Hz and a pressure in the hydraulic loading system of 5-15 MPa [12].

Dynamic parameters of compacting units and particles of the compacted medium are frequency, amplitude, speed, and acceleration. The vibration amplitude of any compactor depends on the physical and mechanical characteristics of the compacted material and changes during its sealing.

The design model of the dynamic model of mixture sealing process by the work tool of the paver is shown in figure 1.

![Figure 1. Dynamic model of the mixture sealing process by the work tool (ramming board, plate, two pressure bars) of the paver.](image)

Where \( m_1 \) – mass of the finishing plate, kg; \( m_2 \) – mass of ramming board, kg; \( m_3 \) – mass of the second pressure bar, kg; \( m_4 \) – mass of the first pressure bar, kg; \( m_5 \) – mass of the mix under the ramming board, kg; \( m_6 \) – mass of the mix under the plate, kg; \( m_7 \) – mass of mix under the first pressure bar, kg; \( m_8 \) – mass of the mix under the second pressure bur, kg; \( k_1 \) – coefficient of elastic reaction of the sealing mix under the plate, N/m; \( c_1 \) – damping coefficient of the sealing mix under the plate, N s/m; \( k_2 \) – coefficient of elastic reaction of the sealing mix under the ramming board, N/m; \( c_2 \) – damping coefficient of the sealing mix under the ramming board, N s/m; \( k_3 \) – coefficient of elastic reaction of the sealing mix under the first pressure bar, N/m; \( c_3 \) – damping coefficient of the sealing mix under the first pressure bar, N s/m; \( k_4 \) – coefficient of elastic reaction of the sealing mix under the second pressure bar, N/m; \( c_4 \) – damping coefficient of the sealing mixture under the second pressure bar, N s/m; \( k_{14} \) and \( k_{13} \) – coefficient of elastic reaction of the first and second pressure bars, N/m; \( c_{14} \) and \( c_{13} \)
– damping coefficient of the first and second pressure bars, N s/m; \( y_1, y_2, y_3 \) and \( y_4 \) – the moving system elements, respectively, m.

We developed a computer model that reflects both the vibration dynamics of structural elements and the rheological properties of the compacted material. Differential equations describing the movement of the first and second pressure bar

\[
(m_1 + m_n) \cdot \ddot{y}_3 - c_{13} \cdot \dot{y}_1 + (c_1 + c_{13}) \cdot \ddot{y}_3 - k_{13} \cdot y_1 + (k_1 + k_{13}) \cdot y_3 = F_3 + m_3 \cdot g + m_9 \cdot g,
\]

\[
(m_4 + m_n) \cdot \ddot{y}_4 - c_{14} \cdot \dot{y}_1 + (c_4 + c_{14}) \cdot \ddot{y}_4 - k_{14} \cdot y_1 + (k_4 + k_{14}) \cdot y_4 = F_4 + m_4 \cdot g + m_4 \cdot g,
\]

where \( F_3, F_4 \) is the force of the second and first pressure bars, respectively, N.

Differential equation of a ramming board

\[
(m_2 + m_9) \cdot \ddot{y}_2 + c_2 \cdot \dot{y}_2 + k_2 \cdot y_2 = F_2 + m_3 \cdot g,
\]

where \( F_2 \) is the force of the ramming board, N.

Taking into account the principle of relative motion, we obtain an additional equation

\[
y_2 = y_1 + e \cdot \sin(\omega_2 \cdot t),
\]

where \( e \) is the size of the gear eccentricity of the ramming board, m; \( \omega_2 \) is the angular rotation speed of the ramming board gear, rad/s; \( \omega_2 = 2 \cdot \pi \cdot f_2 \); \( f_2 \) is the oscillation frequency of ramming board, Hz; \( t \) is the time, s.

Substituting equation (4) in (3) with transformations, we get the following equation

\[
F_2 = (m_2 + m_9) \cdot \ddot{y}_2 + c_2 \cdot \dot{y}_2 + k_2 \cdot y_2 = F_2 + m_3 \cdot g.
\]

Differential equation of the finishing plate motion

\[
(m_1 + m_n) \cdot \ddot{y}_1 + (c_1 + c_{13} + c_{14}) \cdot \dot{y}_1 - c_2 \cdot \ddot{y}_2 - c_{13} \cdot \dot{y}_3 - c_{14} \cdot \dot{y}_4 - k_1 \cdot \dot{y}_1 - k_{13} \cdot y_3 - k_{14} \cdot y_4 = -F_3 - F_4 + (m_3 + m_9) \cdot g.
\]

Moving equation (5) to (6), we get the following differential expression

\[
(m_1 + m_n + m_2 + m_3) \cdot \ddot{y}_1 + (c_1 + c_2 + c_{13} + c_{14}) \cdot \dot{y}_1 - c_{13} \cdot \dot{y}_3 - c_{14} \cdot \dot{y}_4 + (k_1 + k_2 + k_{13} + k_{14}) \cdot y_3 - k_{13} \cdot \dot{y}_3 - k_{14} \cdot y_4 = -F_3 - F_4 + ((m_3 + m_9) \cdot e \cdot \omega_2^2 - k_2 \cdot e) \cdot \sin(\omega_2 \cdot t) + (m_3 + m_9 + m_6) \cdot g.
\]

3. Model in the state space

The state space method allows us to represent the control system as a system of equations [9, 10]:

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

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

Here, \( x(t), u(t) \) and \( y(t) \), represent the states, inputs and outputs respectively, while \( A(t), B(t), C(t) \) and \( D(t) \) are the state-space matrices.

The system state parameters are defined as follows: \( x_1 \) – vertical movement of the plate, \( x_2 \) – vertical velocity of the plate, \( x_3 \) – vertical movement of the first pressure bar, \( x_4 \) – vertical velocity of the first pressure bar, \( x_5 \) – vertical movement of the second pressure bar, \( x_6 \) – vertical velocity of the second pressure bar, \( x_7 \) – vertical movement of the ramming board, \( x_8 \) – vertical velocity of the ramming board.
After transformations of the system of equations (1) - (7), we obtain a mathematical description of the object's dynamics in the Cauchy form:

\[
x_2 = y_1; \quad \dot{x}_2 = \frac{1}{m_1 + m_2} \left( c_{13} \cdot x_2 - (c_{13} + c_{14}) \cdot x_1 + k_{14} \cdot x_4 - (k_{14} + k_{13}) \cdot x_3 + F_3 + (m_3 + m_4) \cdot g \right); \\
x_4 = y_2; \quad \dot{x}_4 = \frac{1}{m_4 + m_5} \left( c_{14} \cdot x_2 - (c_{14} + c_{15}) \cdot x_1 + k_{15} \cdot x_4 - (k_{15} + k_{14}) \cdot x_3 + F_4 + (m_4 + m_5) \cdot g \right).
\]

Moving these parameters to the corresponding vector and matrix allows you to get the following results. Input the notations

\[
M = m_1 + m_2 + m_3; \quad K = k_1 + k_2 + k_3 + k_4; \quad Q = c_1 + c_13 + c_14.
\]

Then the model of the process under study in the state space, in vector-matrix form

\[
\begin{bmatrix}
  x_1(t) \\
  x_2(t) \\
  x_3(t) \\
  x_4(t) \\
  x_5(t) \\
  x_6(t)
\end{bmatrix} =
\begin{bmatrix}
  0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 \\
  -k_{14} & c_{14} & 0 & 0 & 0 & 1 \\
  0 & 0 & 0 & 0 & 0 & 1 \\
  -k_{15} & c_{15} & 0 & 0 & 0 & 1 \\
  0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x_1(t) \\
  x_2(t) \\
  x_3(t) \\
  x_4(t) \\
  x_5(t) \\
  x_6(t)
\end{bmatrix} + \begin{bmatrix}
  u(t)
\end{bmatrix};
\]

\[
\begin{bmatrix}
y_1(t) \\
y_2(t) \\
y_3(t) \\
y_4(t) \\
y_5(t) \\
y_6(t)
\end{bmatrix} =
\begin{bmatrix}
  1 & 0 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x_1(t) \\
  x_2(t) \\
  x_3(t) \\
  x_4(t) \\
  x_5(t) \\
  x_6(t)
\end{bmatrix} + \begin{bmatrix}
  u(t)
\end{bmatrix};
\]

\[
u(t) =
\begin{bmatrix}
-F_3 - F_4 + ((m_2 + m_3) \cdot e \cdot \omega_2^2 - k_2 \cdot e) \cdot \sin(\omega_2 \cdot t) - c_2 \cdot e \cdot \omega_2 \cdot \sin(\omega_2 \cdot t + \frac{\pi}{2}) + (m_3 + m_4 + m_5) \cdot g \\
F_3 + (m_3 + m_4) \cdot g \\
F_4 + (m_4 + m_5) \cdot g
\end{bmatrix}.
\]

4. Research of a computer model

A simulation model was obtained in the MATLAB/Simulink program. The initial data from the scientific work [13] was used to model the process

\[k_1 = 4 \times 10^6 \text{N/m}; k_2 = 8.5 \times 10^9 \text{N/m}; k_3 = 1.8 \times 10^9 \text{N/m}; k_4 = 1.1 \times 10^7 \text{N/m}; k_5 = 1.1 \times 10^7 \text{N/m}; k_6 = 1.1 \times 10^7 \text{N/m}; k_7 = 1.1 \times 10^7 \text{N/m};
\]

\[c_1 = 3200 \text{N/s/m}; c_2 = 1200 \text{N/s/m}; c_3 = 1200 \text{N/s/m}; c_4 = 1200 \text{N/s/m}; c_5 = 1200 \text{N/s/m}; c_6 = 1200 \text{N/s/m};
\]

\[m = 21.6 \text{kg}; m_1 = 682 \text{kg}; m_2 = 71.3 \text{kg}; m_3 = 150 \text{kg}; m_4 = 250 \text{kg}; m_5 = 0.1 \text{m}; m_6 = 0.2 \text{m}; m_7 = 0.2 \text{m};
\]

\[m_8 = 0.2 \text{m}; e = 0.006 \text{m}; \omega_2 = 2 \cdot \pi \cdot f_2, \text{rad/s}; f_2 = 15 \text{Hz}; f_3 = 25 \text{Hz}; f_4 = 9000 \text{N}; f_5 = 9000 \text{N}.
\]
The simulation model of the process under study is shown in figure 2. As a result of computer simulation, graphs of time dependencies of sealing workflow dynamic parameters of the screed, bar 1, bar 2 are obtained: displacement; velocity; acceleration.

![Figure 2. Simulation model in MATLAB/Simulink.](image)

Figure 2. Simulation model in MATLAB/Simulink.

Figure 3 shows the graphical dependencies of the oscillating process parameters of the finishing plate and pressure bars of the paver.

![Figure 3. Graphical dependencies of the oscillating process parameters of the finishing plate and pressure bars of the paver.](image)

Figure 3. Graphical dependencies of the oscillating process parameters of the finishing plate and pressure bars of the paver.

The obtained dependences correspond to the oscillatory process, and signs of stability of the dynamic system are observed. Acceleration of the plate with peak values up to 35 m/s², which indicates a good correlation with the results of studies [1], [13]. The transfer functions (TF) of the research object for the output signals of displacement, speed and acceleration of the screed and the pressure bars are obtained. They look right. The simulation results showed good reproducibility of the process.
5. Conclusion
This article considers modeling problem of highly-efficient object of constant non-destructive compaction testing. There was obtained the computer model of the process of sealing a mixture by highly-efficient work tool of pave train by state space method. There was done the test of obtained model by simulation modelling under MATLAB/Simulink environment. The results of the work are the stage of scientific research in the field of designing intelligent control and control systems for cyber-physical road construction systems.

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