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Realization of optimal motion jerky mode for roller forming unit

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Abstract. The optimal jerky mode of the reciprocating motion for a forming trolley is calculated to increase the reliability and durability of the roller forming unit. The criterion action is used as a criterion of the motion mode, which is an integral over time with the sub-integral function that expresses the jerk's «energy» when calculating the optimal motion jerky mode. The change functions of the kinematic characteristics for the forming trolley are calculated. The variation law of the compaction rollers angular velocity is calculated by taking into account the change functions of the forming trolley speed. The roller forming unit design with a drive from the high-torque stepper motor is proposed, which is mounted in the compaction rollers of the forming trolley and provides the optimal jerky mode of reciprocating motion for the forming trolley. The surface quality of the processed concrete mixture is increased, dynamic loads in the drive mechanism elements are reduced, unnecessary destructive loads on the frame construction are disappeared and, accordingly, the reliability and durability of the unit as a whole are increased, when we use the such drive in the unit.

Keywords: unit, forming trolley, motion mode, drive, speed, acceleration, jerk, stepper motor.

INTRODUCTION

The considerable dynamic loads in the elements of the drive mechanism and the elements of the forming trolleys take place in the roller forming units of reinforced concrete products during operation [1–9]. The motion dynamics of the forming trolley and its influence on the forming process have not yet been researched, despite the rather wide study of the technological process for forming reinforced concrete products by the vibration-free roller method [1–5]. Attended little attention to the forces, which take place in the elements of the drive mechanism and the forming trolley.

The available theoretical and experimental studies of roller forming machines for reinforced concrete products substantiate their design parameters and performance [1–5]. At the same time, attended insufficient attention to the research of active dynamic loads and motion modes, which significantly affects the operation of the unit and the quality of finished products. Significant dynamic loads take place in the elements of the drive mechanism and the elements of the forming trolley during constant start-braking motion modes, which can lead to unit premature failure [6–9]. Thus, the drive mechanism updating of the roller forming unit to ensure such the motion mode of the forming trolley is the actual task, in which the dynamic loads are reduced in the unit elements and the unit durability is increased.

PURPOSE OF THE PAPER

The paper's purpose is to update the drive mechanism design of the roller forming unit to increase its reliability and durability.

RESEARCH RESULTS

The criteria for the motion mode of mechanisms and machines can be coefficients of the motion unevenness and the dynamism [10]. The criterion action is used as a criterion of the motion mode in this paper, which is an integral over time with the sub-integral function that expresses the motion measure or the system action. The optimality motion criterion for the optimal motion jerky mode will be in the form:

$$I_W = \int_0^{t_1} W\,dt \to \min, \qquad (1)$$

where:
t – time; t_1 – duration of the trolley motion from one extreme position to another; W – jerk's «energy» of:

$$W = \frac{1}{2} \cdot m \cdot \dddot{x}^2, \qquad (2)$$

where:
m – mass of the forming trolley; $\dddot{x}$ – jerk (acceleration of the second-order).

The minimum condition of criterion (1) is the Poisson equation:

$$\frac{\partial W}{\partial x} - \frac{d}{dt}\frac{\partial W}{\partial \dot{x}} + \frac{d^2}{dt^2}\frac{\partial W}{\partial \ddot{x}} - \frac{d^3}{dt^3}\frac{\partial W}{\partial \dddot{x}} = 0, \qquad (3)$$

where
x, $\dot{x}$, $\ddot{x}$ – coordinate of the displacement, speed and acceleration respectively.

We can write from expression (3):

$$\begin{gathered} \frac{\partial W}{\partial x} = \frac{\partial W}{\partial \dot{x}} = \frac{\partial W}{\partial \ddot{x}} = 0; \\ \frac{\partial W}{\partial \dddot{x}} = m \cdot \dddot{x}; \\ \frac{d^3}{dt^3}\frac{\partial W}{\partial \dddot{x}} = m \cdot \overset{VI}{x} = 0. \end{gathered} \qquad (4)$$

We get the differential equation and its solutions from the last equation (4):

$$\begin{gathered} \overset{VI}{x} = 0; \quad \overset{V}{x} = C_1; \quad \overset{IV}{x} = C_1 \cdot t + C_2; \\ \dddot{x} = \frac{1}{2} \cdot C_1 \cdot t^2 + C_2 \cdot t + C_3; \\ \ddot{x} = \frac{1}{6} \cdot C_1 \cdot t^3 + \frac{1}{2} \cdot C_2 \cdot t^2 + C_3 \cdot t + C_4; \\ \dot{x} = \frac{1}{24} \cdot C_1 \cdot t^4 + \frac{1}{6} \cdot C_2 \cdot t^3 + \frac{1}{2} \cdot C_3 \cdot t^2 + \\ + C_4 \cdot t + C_5; \\ x = \frac{1}{120} \cdot C_1 \cdot t^5 + \frac{1}{24} \cdot C_2 \cdot t^4 + \frac{1}{6} \cdot C_3 \cdot t^3 + \\ + \frac{1}{2} \cdot C_4 \cdot t^2 + C_5 \cdot t + C_6, \end{gathered} \qquad (5)$$

where:
C_1, C_2, C_3, C_4, C_5, C_6 – constant integrations, which are determined from the boundary conditions.

The boundary conditions for the trolley motion from one extreme position to another: initial – $t = 0$, $x = x_0$, $\dot{x} = 0$, $\ddot{x} = 0$; final – $t = t_1$, $x = x_1$, $\dot{x} = 0$, $\ddot{x} = 0$. Here x_0 and x_1 – the coordinates of the extreme positions for the mass trolleys center. We get, if the boundary conditions substitute into equation (5):

$$t = 0: \quad C_6 = x_0; \quad C_5 = 0; \quad C_4 = 0; \qquad (6)$$

$$t = t_1: \quad \begin{cases} \frac{1}{120} \cdot C_1 \cdot t_1^5 + \frac{1}{24} \cdot C_2 \cdot t_1^4 + \\ + \frac{1}{6} \cdot C_3 \cdot t_1^3 + x_0 = x_1; \\ \frac{1}{24} \cdot C_1 \cdot t_1^4 + \frac{1}{6} \cdot C_2 \cdot t_1^3 + \\ + \frac{1}{2} \cdot C_3 \cdot t_1^2 = 0; \\ \frac{1}{6} \cdot C_1 \cdot t_1^3 + \frac{1}{2} \cdot C_2 \cdot t_1^2 + C_3 \cdot t_1 = 0. \end{cases} \qquad (7)$$

We obtain C_1, C_2 and C_3 constant integrations after solving the equations system (7):

$$C_1 = 720 \cdot \frac{(x_1 - x_0)}{t_1^5};$$
$$C_2 = -360 \cdot \frac{(x_1 - x_0)}{t_1^4}; \qquad (8)$$
$$C_3 = 60 \cdot \frac{(x_1 - x_0)}{t_1^3}.$$

We obtain expressions to determine the kinematic characteristics of the forming trolley when its displacement from one extreme position to another in the optimal jerky mode of reciprocating motion if determined constant integrations (6), (8) substitute into equation (5):

$$x = x_0 + (x_1 - x_0) \cdot \left(6 \cdot \frac{t^2}{t_1^2} - 15 \cdot \frac{t}{t_1} + 10\right) \cdot \frac{t^3}{t_1^3};$$
$$\dot{x} = 30 \cdot (x_1 - x_0) \cdot \left(\frac{t^2}{t_1^2} - 2 \cdot \frac{t}{t_1} + 1\right) \cdot \frac{t^2}{t_1^3};$$
$$\ddot{x} = 60 \cdot (x_1 - x_0) \cdot \left(2 \cdot \frac{t^2}{t_1^2} - 3 \cdot \frac{t}{t_1} + 1\right) \cdot \frac{t}{t_1^3}; \qquad (9)$$
$$\dddot{x} = 60 \cdot (x_1 - x_0) \cdot \left(6 \cdot \frac{t^2}{t_1^2} - 6 \cdot \frac{t}{t_1} + 1\right) \cdot \frac{1}{t_1^3}.$$

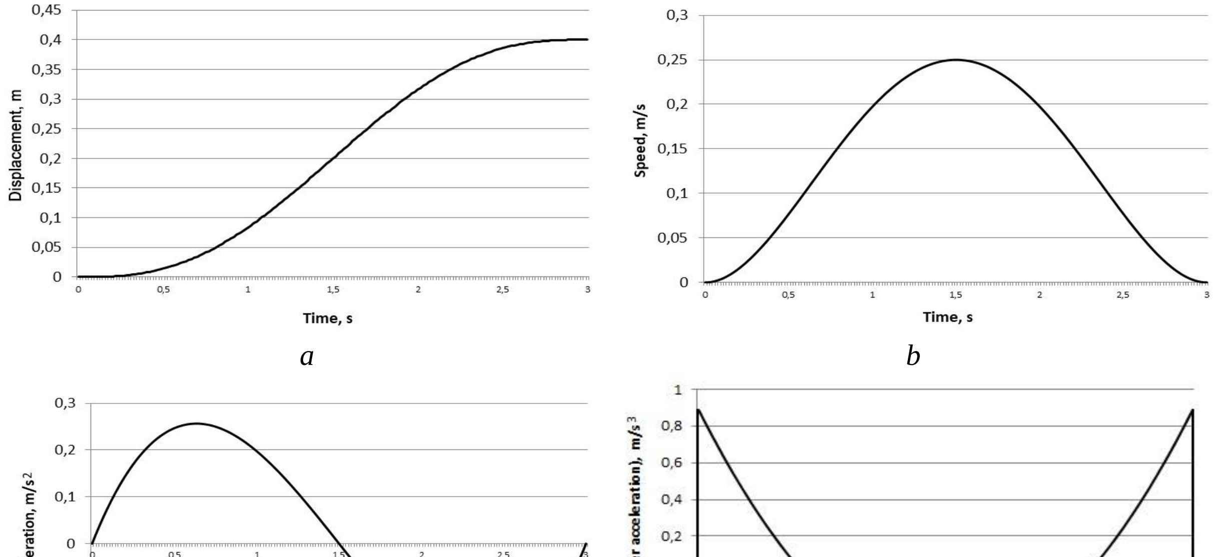
The kinematic characteristics of the optimal motion jerky mode for the forming trolley were calculated when we accepted the displacement amplitude of the forming trolley $\Delta x = x_1 - x_0 = 0,4\,\text{m}$ and the total time of its motion from one extreme position to another $t_1 = 3\,\text{s}$. We built change graphs in displacement (Fig. 1, *a*), speed (Fig. 1, *b*), acceleration (Fig. 2, c), and jerk (second-order acceleration) (Fig. 1, d) on the calculation results during the forming trolley motion from one extreme position to another with the optimal jerky mode.

The motion law of the forming trolley, described by equations (9), can be implemented by driving from the high-torque stepper motor, which is mounted in the compaction rollers of the unit forming trolley. Herewith, the variation law of the angular velocity for the drive stepper motor is described by the equation:

$$\dot{\varphi} = 30 \cdot \frac{\Delta x}{R} \cdot \left(\frac{t^2}{t_1^2} - 2 \cdot \frac{t}{t_1} + 1\right) \cdot \frac{t^2}{t_1^3}, \ 0 \le t \le t_1, (10)$$

where R – radius of compaction rollers.

The variation law of the angular velocity



a *b*

c *d*

Fig. 1. Change graphs in displacement (*a*), speed (*b*), acceleration (*c*) and jerk (*d*) during the optimal motion jerky mode of the forming trolley

for the drive stepper motor is determined during the forming trolley motion in the reverse direction similarly:

$$\dot{\varphi} = -30 \cdot \frac{\Delta x}{R} \cdot \left[\frac{\left(t - t_1\right)^2}{t_1^2} - 2 \cdot \frac{\left(t - t_1\right)}{t_1} + 1 \right] \cdot \frac{\left(t - t_1\right)^2}{t_1^3}, \quad (11)$$

$$t_1 \le t \le 2t_1 .$$

The unit design with the drive mechanism (Fig. 2) is proposed to ensure the optimal jerky mode of reciprocating motion for the forming trolley to reduce the unit elements' dynamic loads and increase its reliability.

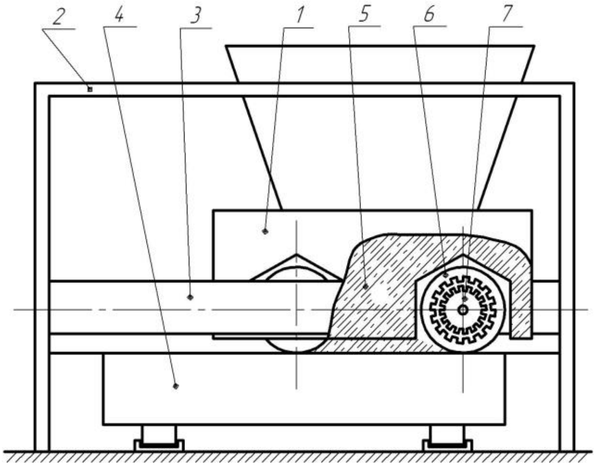


Fig. 2. Roller forming unit with stepper motor drive

The roller forming unit consists of the forming trolley 1, which is mounted on portal 2, and performs the reciprocating motion in guide 3 above the mold cavity 4. The forming trolley has the feeding hopper 5 and compaction rollers 6 on axis 7.

The trolley is reciprocated by means of the high-torque stepper motor, which is mounted in rollers, and the roller axis acts as a stator, and the roller itself acts as a rotor [11].

The surface quality of the processed concrete mixture is increased, dynamic loads in the drive mechanism elements are reduced, unnecessary destructive loads on the frame construction are disappeared and, accordingly, the reliability and durability of the unit as a whole are increased, when we use the drive from the high-torque stepper motor that installed in compaction rollers, the which variation law of the angular velocity is described by above equations.

CONCLUSIONS

The optimal jerky mode of the reciprocating motion for the forming trolley was calculated as the research result, which was carried out to increase the reliability and durability of the roller forming unit. The trolley kinematic characteristics during the optimal jerky mode of reciprocating motion were calculated.

The roller forming unit design with a drive from the high-torque stepper motor, which is mounted in the compaction rollers of the unit forming trolley, is proposed to ensure the optimal jerky mode of the reciprocating motion for the forming trolley.

The paper's results can be useful in the future for the clarification and improvement of the available engineering methods for calculating the drive mechanisms of roller forming machines, both at the design or construction stages and in real operation modes.

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Реалізація оптимального ривкового режиму руху роликової формувальної установки

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Анотація. З метою підвищення надійності та довговічності роликової формувальної установки розраховано оптимальний ривковий режим зворотно-поступального руху формувального візка.

При розрахунку оптимального ривкового режиму руху в якості критерію режиму руху використана критеріальна дія, яка являє собою інтеграл за часом з підінтегральною функцією, що виражає «енергію» ривків. Розраховано функції зміни кінематичних характеристик формувального візка під час його руху від одного крайнього положення до іншого, які відповідають оптимальному ривковому режиму зворотно-поступального руху. При такому режимі руху переміщення, швидкість та прискорення формувального візка змінюються плавно, не створюючи значних динамічних навантажень в установці, що в свою чергу позитивно впливає на її довговічність.

Із врахуванням функцій зміни швидкості формувального візка розраховано закон зміни кутової швидкості обертання його укочувальних роликів. Запропоновано конструкцію роликової формувальної установки з приводом від високомоментного крокового двигуна, що вмонтований в укочувальні ролики формувального візка і забезпечує оптимальний ривковий режим зворотно-поступального руху формувального візка.

При застосуванні в установці вказаного приводу підвищується якість поверхні оброблюваної бетонної суміші, зменшуються динамічні навантаження в елементах приводного механізму, зникають зайві руйнівні навантаження на рамну конструкцію і, відповідно, підвищується надійність та довговічність установки в цілому.

Результати роботи можуть в подальшому бути корисними для уточнення та удосконалення існуючих інженерних методів розрахунку приводних механізмів машин роликового формування як на стадіях проєктування / конструювання, так і в режимах реальної експлуатації. Також результати роботи можуть бути корисними при проєктуванні або удосконаленні механізмів із зворотно-поступальним рухом виконавчих елементів.

Ключові слова: установка, формувальний візок, режим руху, привод, швидкість, прискорення, ривок, кроковий двигун.