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Realization of combined dynamic motion mode for roller forming unit

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Abstract. The combined dynamic 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 acceleration «energy» when calculating the combined dynamic motion mode of the forming trolley in the acceleration and braking areas. The change functions of the kinematic characteristics of the forming trolley during its motion from one extreme position to another, which correspond to the combined dynamic mode of the reciprocating motion, are calculated. The displacement and speed of the forming trolley in the acceleration and braking areas change smoothly with this motion mode, without creating significant dynamic loads in the unit, which in turn has a positive effect on its durability.

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 combined dynamic 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, displacement, speed, acceleration, 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 [1–10]. 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 [6–10].

Thus, the drive mechanism updating of the roller forming unit to ensure such the motion mode of the forming trolley is the actual task [11, 12], 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

Desirable to have a constant speed of reciprocating motion of the forming trolley over the entire section of the roller forming unit when compacting the concrete mixture, which would positively affect the quality of the finished product. However, such the motion mode cannot be realized in practice, since there are no acceleration and braking areas, without which there can be no cyclic motion. We are proposed to realize such the motion mode of the forming trolley during its displacement from one extreme position to another, in which there would be acceleration and braking areas with minimal dynamic loads and the motion section at a constant speed.

It is proposed to perform according to the optimal dynamic motion mode for the smooth acceleration and braking process of the forming trolley [11, 13]. At the same time, the displacement, and speed of the forming trolley change smoothly, without creating significant dynamic loads in the unit, which in turn has a positive effect on its durability.

The criteria for the motion mode of mechanisms and machines can be coefficients of the motion unevenness and a dynamism [11–13]. 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 combined dynamic motion mode will be:

$$I_V = \int_0^{t_1} V\,dt \to \min, \tag{1}$$

where t – time; t_1 – duration of the trolley motion from one extreme position to another; V – acceleration «energy» of:

$$V = \frac{1}{2}\cdot m \cdot \ddot{x}^2, \tag{2}$$

where m – mass of the forming trolley; $\ddot{x}$ – acceleration of the forming trolley.

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

$$\frac{\partial V}{\partial x} - \frac{d}{dt}\frac{\partial V}{\partial \dot{x}} + \frac{d^2}{dt^2}\frac{\partial V}{\partial \ddot{x}} = 0, \tag{3}$$

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

We can write from expression (3):

$$\begin{gathered} \frac{\partial V}{\partial x} = \frac{\partial V}{\partial \dot{x}} = 0; \\ \frac{\partial V}{\partial \ddot{x}} = m \cdot \ddot{x}; \\ \frac{d^2}{dt^2}\frac{\partial V}{\partial \ddot{x}} = m \cdot \overset{IV}{x} = 0. \end{gathered} \tag{4}$$

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

$$\begin{gathered} \overset{IV}{x} = 0; \quad \dddot{x} = C_1; \quad \ddot{x} = C_1 \cdot t + C_2; \\ \dot{x} = \frac{1}{2}\cdot C_1 \cdot t^2 + C_2 \cdot t + C_3; \\ x = \frac{1}{6}\cdot C_1 \cdot t^3 + \frac{1}{2}\cdot C_2 \cdot t^2 + C_3 \cdot t + C_4, \end{gathered} \tag{5}$$

where:
C_1, C_2, C_3, C_4 is constant integrations under boundary conditions.

The boundary conditions for the acceleration area of the forming trolley from the rest moment to the exit in the steady motion mode: $t = 0$: $x = 0$, $\dot{x} = 0$ and $t = t_a$: $\dot{x} = \dot{x}_y$, $\ddot{x} = 0$. Here t_a – the acceleration duration of the forming trolley from the rest moment to the exit in the steady motion mode; $\dot{x}_y$ – the trolley speed in the steady mode.

We get, if the boundary conditions substitute into equation (5):

$$t = 0: \quad C_4 = 0; \quad C_3 = 0; \tag{6}$$

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$$t = t_a: \quad \begin{cases} \frac{1}{2} \cdot C_1 \cdot t_a^2 + C_2 \cdot t_a + C_3 = \dot{x}_y; \\ C_1 \cdot t_a + C_2 = 0. \end{cases} \quad (7)$$

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

$$C_1 = -2 \cdot \frac{\dot{x}_y}{t_a^2}; \quad C_2 = 2 \cdot \frac{\dot{x}_y}{t_a}. \quad (8)$$

We obtain expressions to determine the kinematic characteristics of the forming trolley during acceleration from the rest moment to the exit in the steady motion mode if determined constant integrations (6) and (8) substitute into equation (5):

$$\begin{aligned} x_a &= x_{0a} - \dot{x}_y \cdot \left(\frac{1}{3} \cdot \frac{t^3}{t_a^2} - \frac{t^2}{t_a} \right); \\ \dot{x}_a &= -\dot{x}_y \cdot \left(\frac{t^2}{t_a^2} - 2 \cdot \frac{t}{t_a} \right); \\ \ddot{x}_a &= -2 \cdot \dot{x}_y \cdot \left(\frac{t}{t_a^2} - \frac{1}{t_a} \right); \\ \dddot{x}_a &= -2 \cdot \dot{x}_y \cdot \frac{1}{t_a^2}, \end{aligned} \quad (9)$$

where x_{0a} – coordinate of the initial position for the trolley mass center during acceleration.

The coordinates of displacement, speed, acceleration, and jerk of the mass center for the forming trolley in the steady motion mode are described by the equations [13]:

$$\begin{aligned} x_y &= x_{0y} + \frac{\left(x_{1y} - x_{0y} \right) \cdot t}{t_y}; \\ \dot{x}_y &= \frac{\left(x_{1y} - x_{0y} \right)}{t_y} = const; \\ \ddot{x}_y &= 0; \quad \dddot{x}_y = 0, \end{aligned} \quad (10)$$

where:

x_{0y} and x_{1y} – coordinates of the initial and final positions for the trolley mass center in the steady motion mode; t_y – duration of steady motion.

The boundary conditions for the braking area of the forming trolley are as follows: $t = 0$: $\dot{x} = \dot{x}_y$, $\ddot{x} = 0$ та $t = t_b$: $x = x_{1b}$, $\dot{x} = 0$. Here t_b – the braking duration from the moment of steady motion to the complete stop; x_{1b} – final coordinate of the braking process.

We get, if the boundary conditions substitute into equation (5):

$$t = 0: \quad C_3 = \dot{x}_y; \quad C_2 = 0; \quad (11)$$

$$t = t_b: \quad \begin{cases} \frac{1}{6} \cdot C_1 \cdot t_b^3 + \dot{x}_y \cdot t_b + C_4 = x_{1b}; \\ \frac{1}{2} \cdot C_1 \cdot t_b^2 + \dot{x}_y = 0. \end{cases} \quad (12)$$

We obtain C_1 and C_4 constant integrations after solving the equations system (12):

$$C_1 = -2 \cdot \frac{\dot{x}_y}{t_b^2}; \quad C_4 = x_{1b} - \frac{2}{3} \cdot \dot{x}_y \cdot t_b. \quad (13)$$

We obtain expressions to determine the kinematic characteristics of the forming trolley in the braking from the moment of steady motion to the complete stop if determined constant integrations (11) and (13) substitute into equation (5):

$$\begin{aligned} x_b &= x_{1b} - \dot{x}_y \cdot \left(\frac{1}{3} \cdot \frac{t^3}{t_b^2} - t + \frac{2}{3} \cdot t_b \right); \\ \dot{x}_b &= -\dot{x}_y \cdot \left(\frac{t^2}{t_b^2} - 1 \right); \\ \ddot{x}_b &= -2 \cdot \dot{x}_y \cdot \frac{t}{t_b^2}; \\ \dddot{x}_b &= -2 \cdot \dot{x}_y \cdot \frac{1}{t_b^2}. \end{aligned} \quad (14)$$

The coordinate of the initial position for the trolley mass center during acceleration x_{0a} and the final coordinate of the braking process x_{1b} correspond to its extreme positions in expressions (9), (10), and (14). But the movement speed of the forming trolley $\dot{x}_y$ in the steady mode, and the coordinates of the initial x_{0y} and final x_{1y} positions for the trolley mass center in steady motion are unknown.

Let's divide the displacement of the forming trolley from one extreme position to another into three areas: 1 – acceleration section, displacement corresponds to it S_a; 2 – section of steady motion, displacement corresponds to it S_y; 3 – braking area, displacement corresponds to it S_b. The displacement expressions on each section, into account of dependencies (9), (10) and (14), can be given in the form:

$$S_a = \int_0^{t_a} \dot{x}_a\, dt = \dot{x}_y \cdot \int_0^{t_a} \left(2 \cdot \frac{t}{t_a} - \frac{t^2}{t_a^2} \right) dt = = \dot{x}_y \cdot \left(\frac{t^2}{t_a} - \frac{t^3}{3 \cdot t_a^2} \right)\Bigg|_0^{t_a} = \frac{2}{3} \cdot \dot{x}_y \cdot t_a ; \quad (15)$$

$$S_y = \int_0^{t_y} \dot{x}_y\, dt = \dot{x}_y \cdot t \Big|_0^{t_y} = \dot{x}_y \cdot t_y ; \quad (16)$$

$$S_b = \int_0^{t_b} \dot{x}_b\, dt = \dot{x}_y \cdot \int_0^{t_b} \left(1 - \frac{t^2}{t_b^2} \right) dt = = \dot{x}_y \cdot \left(t - \frac{t^3}{3 \cdot t_b^3} \right)\Bigg|_0^{t_b} = \frac{2}{3} \cdot \dot{x}_y \cdot t_b . \quad (17)$$

Then the expression of the general motion for the forming trolley can be written:

$$S = S_a + S_y + S_b = = \frac{2}{3} \cdot \dot{x}_y \cdot t_a + \dot{x}_y \cdot t_y + \frac{2}{3} \cdot \dot{x}_y \cdot t_b = = \dot{x}_y \cdot \left(\frac{2}{3} \cdot t_a + t_y + \frac{2}{3} \cdot t_b \right). \quad (18)$$

To ensure the compaction of the concrete mixture by the forming trolley with constant movement speed over most of its working stroke, we will take the steady motion time, for example, $t_y = \frac{2}{3} \cdot t_t$, where t_t – the movement total time of the forming trolley from one extreme position to another. Then they can be determined by the corresponding expressions, given the condition of equal acceleration and deceleration time: $t_a = \frac{1}{6} \cdot t_t$ and $t_b = \frac{1}{6} \cdot t_t$.

Substituting $t_a = \frac{1}{6} \cdot t_t$, $t_y = \frac{2}{3} \cdot t_t$, $t_b = \frac{1}{6} \cdot t_t$ and the displacement amplitude of the trolley from one extreme position to another $\Delta x = S$ in expression (18), we obtain:

$$\Delta x = \dot{x}_y \cdot \left(\frac{2}{3} \cdot \frac{1}{6} \cdot t_t + \frac{2}{3} \cdot t_t + \frac{2}{3} \cdot \frac{1}{6} \cdot t_t \right) = \frac{8}{9} \cdot \dot{x}_y \cdot t_t \quad \Rightarrow \quad \dot{x}_y = \frac{9 \cdot \Delta x}{8 \cdot t_t}. \quad (19)$$

We can determine the position coordinate of the forming trolley that determines the end of the acceleration section and the start of the steady motion section x_{0y} from expressions (15) and (19):

$$x_{0y} = \frac{2}{3} \cdot \dot{x}_y \cdot t_a = \frac{2}{3} \cdot \frac{9 \cdot \Delta x}{8 \cdot t_t} \cdot \frac{1}{6} \cdot t_t = \frac{1}{8} \cdot \Delta x , \quad (20)$$

and we can determine the coordinate that determines the end of the steady motion section x_{1y} and the start of the braking section from expressions (16), (19) and (20):

$$x_{1y} = x_{0y} + \dot{x}_y \cdot t_y = = \frac{1}{8} \cdot \Delta x + \frac{9 \cdot \Delta x}{8 \cdot t_t} \cdot \frac{2}{3} \cdot t_t = \frac{7}{8} \cdot \Delta x. \quad (21)$$

We present the kinematic characteristics of the forming trolley in the areas of acceleration, steady motion and braking, substituting expressions (19)...(21) into equations (9), (10) and (14), and assuming $t_a = \frac{1}{6} \cdot t_t$, $t_y = \frac{2}{3} \cdot t_t$, $t_b = \frac{1}{6} \cdot t_t$:

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$$\begin{aligned}
x_a &= \frac{27}{4}\cdot\Delta x\cdot\left(1-2\cdot\frac{t}{t_t}\right)\cdot\frac{t^2}{t_t^2};\\
\dot{x}_a &= \frac{27}{2}\cdot\Delta x\cdot\left(1-3\cdot\frac{t}{t_t}\right)\cdot\frac{t}{t_t^2};\\
\ddot{x}_a &= \frac{27}{2}\cdot\Delta x\cdot\left(1-6\cdot\frac{t}{t_t}\right)\cdot\frac{1}{t_t^2};\\
\dddot{x}_a &= -81\cdot\Delta x\cdot\frac{1}{t_t^3};
\end{aligned}\qquad(22)$$

$$\begin{aligned}
x_y &= \frac{1}{8}\cdot\Delta x\cdot\left(9\cdot\frac{t}{t_t}+1\right);\\
\dot{x}_y &= \frac{9\cdot\Delta x}{8\cdot t_t}=const;\\
\ddot{x}_y &= 0;\quad \dddot{x}_y = 0;
\end{aligned}\qquad(23)$$

$$\begin{aligned}
x_b &= \Delta x-\frac{9}{8}\cdot\Delta x\cdot\left(12\cdot\frac{t^3}{t_t^3}-\frac{t}{t_t}+\frac{1}{9}\right);\\
\dot{x}_b &= \frac{9}{8}\cdot\Delta x\cdot\left(\frac{1}{t_t}-36\cdot\frac{t^2}{t_t^3}\right);\\
\ddot{x}_b &= -81\cdot\Delta x\cdot\frac{t}{t_t^3};\quad \dddot{x}_b = -81\cdot\Delta x\cdot\frac{1}{t_t^3}.
\end{aligned}\qquad(24)$$

The kinematic characteristics of the combined dynamic motion mode for the forming trolley were calculated when we have given the displacement amplitude of the forming trolley $\Delta x = 0,4$ m and the total time $t_t = 3$ s of its movement from one extreme position to another on expressions (22)…(24).

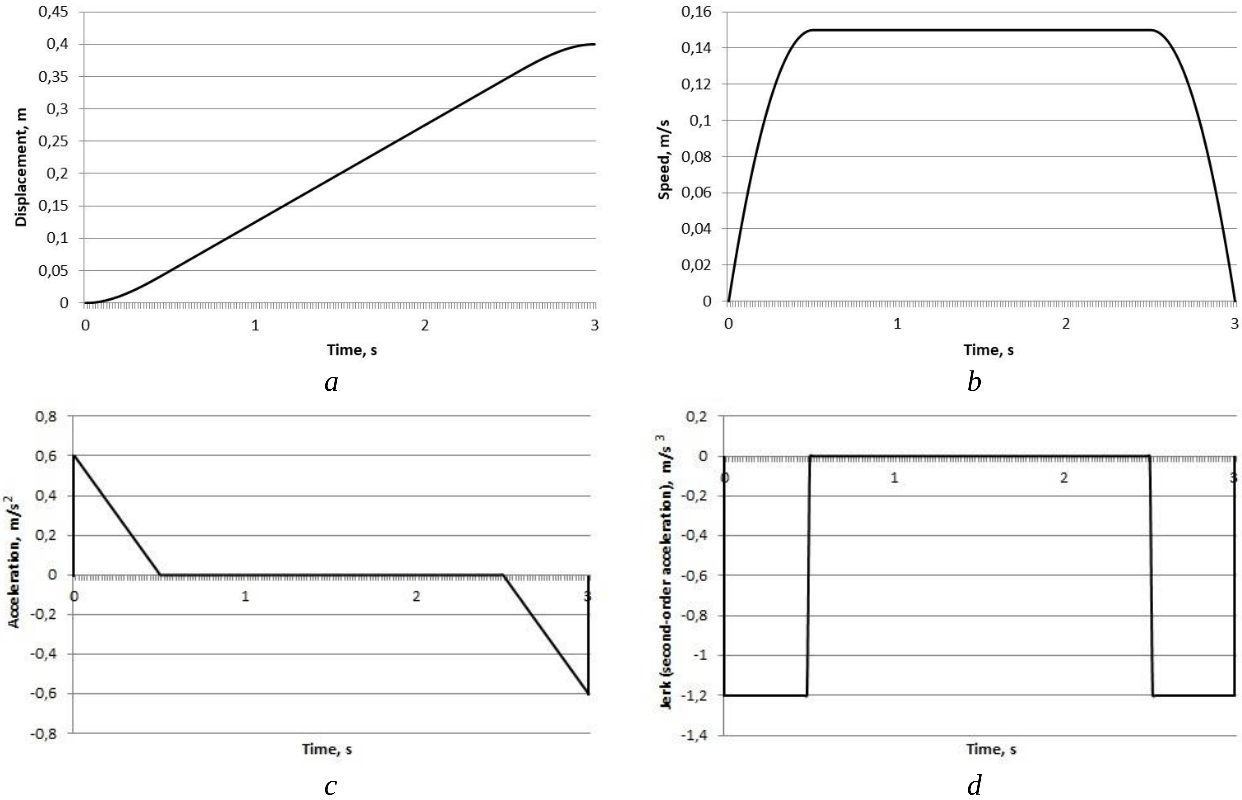

Fig. 1. Change graphs in displacement (*a*), speed (*b*), acceleration (*c*) and jerk (*d*) during the combined dynamic motion mode of the forming trolley

We built change graphs in displacement (Fig. 1, a), speed (Fig. 1, b), acceleration (Fig. 1, c), and jerk (second-order acceleration) (Fig. 1, d) on the calculation results during the trolley motion from one extreme position to another.

The motion law of the forming trolley, described by equations (22)…(24), can be realized by driving from the high-torque stepper motor, which is mounted in the compaction rollers. Herewith, the variation law of the angular velocity for the drive stepper motor is described by equations:

– in the acceleration section

$$\dot{\varphi}_a = \frac{1}{R} \cdot \frac{27}{2} \cdot \Delta x \cdot \left(1 - 3 \cdot \frac{t}{t_t}\right) \cdot \frac{t}{t_t^2}; \qquad (25)$$

– in the section of steady motion

$$\dot{\varphi}_y = \frac{1}{R} \cdot \frac{9 \cdot \Delta x}{8 \cdot t_t}; \qquad (26)$$

– in the braking area

$$\dot{\varphi}_b = \frac{1}{R} \cdot \frac{9}{8} \cdot \Delta x \cdot \left(\frac{1}{t_t} - 36 \cdot \frac{t^2}{t_t^3}\right), \qquad (27)$$

where R – radius of compaction rollers.

We obtain the variation law in the angular velocity of the drive stepper motor during the movement of the forming trolley from one extreme position to another, taking the acceleration time of the forming trolley $t_a = \frac{1}{6} \cdot t_t$, the time of steady motion – $t_y = \frac{2}{3} \cdot t_t$ and the braking time – $t_b = \frac{1}{6} \cdot t_t$:

$$\dot{\varphi} = \frac{27 \cdot \Delta x}{2 \cdot R} \cdot \left(1 - 3 \cdot \frac{t}{t_t}\right) \cdot \frac{t}{t_t^2}, \quad 0 \le t \le \frac{1}{6} t_t; \qquad (28)$$

$$\dot{\varphi} = \frac{9 \cdot \Delta x}{8 \cdot R \cdot t_t}, \quad \frac{1}{6} t_t < t < \frac{5}{6} t_t; \qquad (29)$$

$$\dot{\varphi} = \frac{9 \cdot \Delta x}{8 \cdot R} \cdot \left(\frac{1}{t_t} - 36 \cdot \left(t - \frac{5}{6} t_t\right)^2 \cdot \frac{1}{t_t^3}\right), \quad \frac{5}{6} t_t < t \le t_t. \qquad (30)$$

The variation law of the angular velocity for the drive stepper motor is determined during the forming trolley motion in the reverse direction similarly:

$$\dot{\varphi} = \frac{27 \cdot \Delta x}{2 \cdot R} \cdot \left(3 \cdot \frac{(t - t_t)}{t_t} - 1\right) \cdot \frac{(t - t_t)}{t_t^2}, \quad t_t \le t \le \frac{7}{6} t_t; \qquad (31)$$

$$\dot{\varphi} = -\frac{9 \cdot \Delta x}{8 \cdot R \cdot t_t}, \quad \frac{7}{6} t_t < t < \frac{11}{6} t_t; \qquad (32)$$

$$\dot{\varphi} = \frac{9 \cdot \Delta x}{8 \cdot R} \cdot \left(36 \cdot \left(t - \frac{11}{6} t_t\right)^2 \cdot \frac{1}{t_t^3} - \frac{1}{t_t}\right), \quad \frac{11}{6} t_t < t \le 2 t_t. \qquad (33)$$

The unit design with the drive mechanism from the high-torque stepper motor is proposed to ensure the combined dynamic mode of reciprocating motion for the forming trolley to reduce the unit elements' dynamic loads and increase its reliability (Fig. 2).

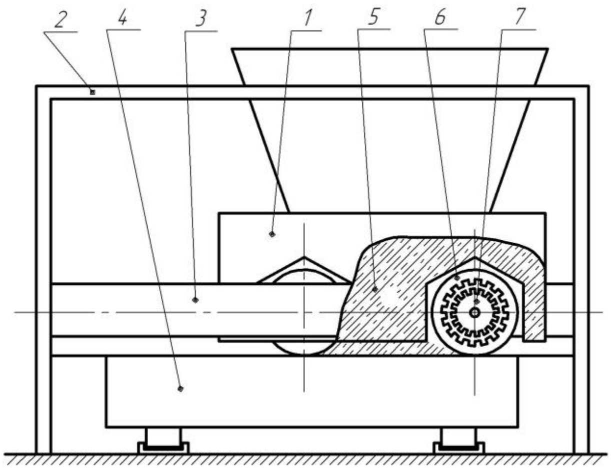

Fig. 2. Roller forming unit with stepper motor drive

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 [14].

The surface quality of the processed concrete mixture is increased, dynamic loads in the drive mechanism elements are reduced,

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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 combined dynamic 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 combined dynamic 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 combined dynamic 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 комбінованого динамічного режиму руху роликової формувальної установки

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Анотація. З метою підвищення надійності та довговічності роликової формувальної установки розраховано комбінований динамічний режим зворотно-поступального руху формувального візка. При розрахунку комбінованого динамічного режиму руху формувального візка на ділянках розгону та гальмування в якості критерію режиму руху використана критеріальна дія, яка являє собою інтеграл за часом з підінтегральною функцією, що виражає «енергію» прискорень. Розраховано функції зміни кінематичних характеристик формувального візка під час його руху від одного крайнього положення до іншого, які відповідають комбінованому динамічному режиму зворотно-поступального руху. При такому режимі руху переміщення та швидкість формувального візка на ділянках розгону та гальмування 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 комбінований динамічний 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, переміщення, швидкість, прискорення, кроковий двигун.