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Mathematical model of the road vibrating roller

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Annotation

Introduction. The process of compaction of the soil foundation by a road vibrating roller is considered as the object of the study. The main purpose of vibrating rollers used in road construction is to reduce the energy consumption of the compaction process and increase the productivity of the operations performed Since the 80s of the last century, the engineering industry has noted a tendency to abstention the production of static rollers. By reducing the amplitude of oscillations or completely disconnecting the vibrator, you can get the same static modes, and accordingly the results of rolling. In addition, the reduction of dynamic impacts positively affects the physical condition of an operator of the road-building machine, stabilizes the well-being and increases productivity.

Materials and methods. The mathematical model of the dynamic system "Supporting surface–roller–operator" is presented. The main components of the dynamic system are described in the form of ordered and interacting subsystems. The forces acting on the dynamic system are determined; they are sources of dynamic effects. The calculation schemes of the subsystems "Operator" and "Roller", which are of the greatest interest from the point of view of vibration protection, are reflected.

Results. The result of the work can be considered the compilation of generalized scheme of the dynamic system; calculation scheme of the dynamic system; mathematical model "Supporting surface–operator–roller"; implementation of the mathematical model in MathLab, its additional Simulink extension package.

Discussion and conclusion. The presented mathematical model allows carrying out research of the processes occurring in the dynamic system "Supporting surface–roller–operator". The most rational mathematical model can be used in the development of methods and tools aimed at improving the vibration protection system for operators of road rollers. The mathematical model of a road roller is planned to be used as a basis for creating a robotic complex with an automated control system designed to perform operations to compact coatings and foundations in road construction.

Keywords: road-building machines, road roller, mathematical modeling, vibration protection systems, vibration.

Introduction

An increase in the share of roads of regional and federal significance that meet regulatory requirements, a decrease in the share of roads of federal and regional significance operating in overload mode are the priority tasks of the development strategy of the Russian Federation implemented within the framework of the national project called "Safe and high-quality roads". The solution to these problems implies the need not only to overhaul existing roads, but to build new ones as well.

One of the main factors affecting the life of roads is the high-quality compaction of the subgrade, pavement. Road roller is a common compacting machine with versatility and development prospects [1].

Vibratory rollers are most effective for lowly cohesive materials [1, 2] because compaction occurs through energy pulses. In addition, in vibratory rollers, the dynamic load is combined with the static load from the rolls. Vibration significantly eliminates internal friction in the mixture and improves the compaction effect, even if rollers with relatively low static linear loads are used [3].

Positive vibration effect, from the point of view of the compaction process, negatively affects the health of an operator. The conducted studies have shown that prolonged vibration exposure leads to increased operator fatigue, an increase in the number of errors made, reduced labor productivity, and leads to the development of vibration disease in the long term [1, 4].

Research objective

It is possible to increase the performance of a road vibration roller by reducing the vibration effect on the operator's workplace, or by creating a robotic machine – a road roller. The method of mathematical modeling allows significantly simplifying the solution of these problems. Existing mathematical models were created, as a rule, to study the process of compaction or movement of the roller, and they do not include an operator model. Therefore, to solve some problems of vibration

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protection, it is necessary to develop new mathematical models that take into account the biomechanical characteristics of an operator.

Materials and methods

Using the decomposition method allows us to represent the dynamic system “Supporting surface–roller–operator” in the form of orderly interacting subsystems: “Supporting surface”, “Roller” and “Operator” (Fig. 1). In turn, the dynamic subsystem “Roller” can be divided into a number of simpler subsystems: “Internal combustion engine”, “Vibration exciter”, “Metallic structure of a roller”. The subsystems “Internal combustion engine” and “Vibration exciter” are sources of dynamic impact. The subsystems “Metallic structure of a roller” and “Supporting surface” contribute to further vibration from the source to the object of vibration protection: “Operator” subsystem [1, 5].

When performing work operations, the roller operator is in a sitting position on a specially equipped chair having an elastic-viscous suspension [4, 6]. The analysis of previous works has showed that a single-mass mathematical model can be used for solving problems of reducing dynamic effects (including at the operator’s workplace) with its mathematical description (Fig. 2).

The equation describing the behavior of such a model has the form [7]:

$$m\ddot{q} + b\dot{q} + cq = Q, \qquad (1)$$

where m is the mass of an operator participating in the oscillations; $q, \dot{q}, \ddot{q}$ – respectively, the generalized coordinate, speed and acceleration; b is the damping coefficient; c is the stiffness coefficient; Q – disturbing force.

The values of coefficients of differential equation (1) for the average operator of road-building machines can be equal to: $m = 70$ kg, $c = 5{,}63 \times 10^4$ N/m, $b = 523$ (N × s)/m [8]. Since the roller operator is in a sitting position, the chair accounts for 75% of its body weight, and 25% of the body weight must be taken into account when modeling the part of the roller on which its legs rest [8, 9].

Sources of dynamic effects of the vibratory roller are an internal combustion engine and a vibration exciter. The internal combustion engine is a source of a periodic signal, therefore, a source of periodic vibration. Such a signal can be represented in the form of Fourier series [1, 10]:

$$\vec{F} = \sum_{i=1}^{n} A_i \cdot \cos(\omega_i \cdot t + \varphi_i).$$

The vibration exciter of the vibratory roller generates monoharmonic vibrations, the frequency of which is directly proportional to the number of revolutions of the motor shaft. The kinematic scheme of the roller provides a rigid connection between the output shaft of the engine and the shaft of the exciter. So,

$$\frac{n_{\text{DVS}}}{n_{\text{VV}}} = U_{\text{PR}},$$

where n_{DVS} is the engine speed, rpm; n_{VV} – speed of the shaft of the vibrating agent, rpm; U_{PR} – transmission ratio of the drive of the vibrating exciter.

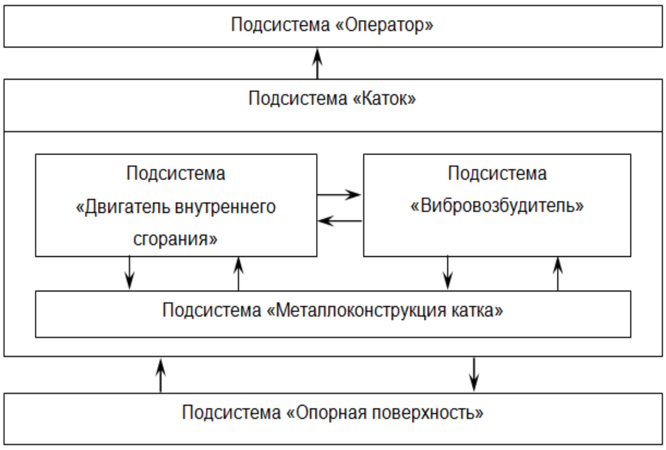

Figure 1. Block diagram of the dynamic system “Support surface–skating rink–operator”.
Рисунок 1. Блок-схема динамической системы «Опорная поверхность–каток–оператор».

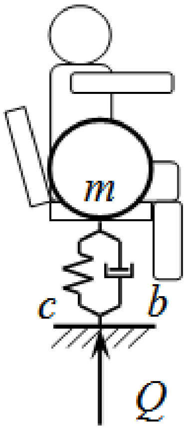

Figure 2. Calculation scheme of the subsystem “Operator”.
Рисунок 2. Расчетная схема подсистемы «Оператор».

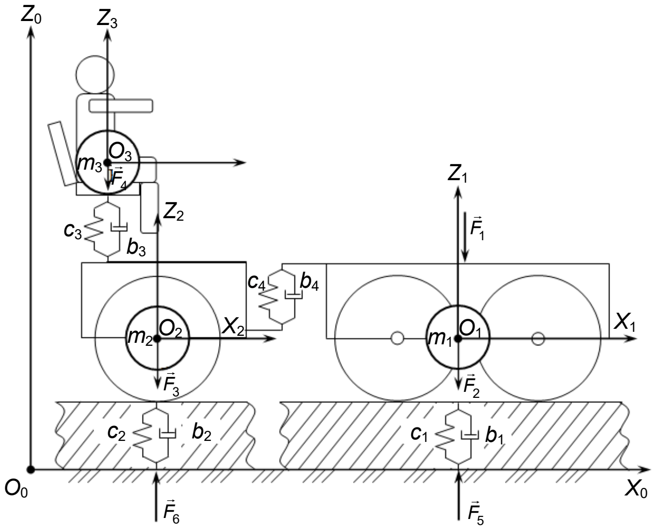

Figure 3. The calculation scheme of the dynamic system “Support surface–skating rink–operator”.
Рисунок 3. Расчетная схема динамической системы «Опорная поверхность–каток–оператор».

A diverse fleet of rollers is used in the construction industry. Currently, vibratory rollers with smooth metal rolls are widely used [4, 11]. As some tests showed, the vibration in the longitudinal and transverse directions is much less than in the vertical. Based on this, a flat design scheme [2, 12] can be used to solve the problems posed. When compiling a generalized calculation scheme of a dynamic system, the following assumptions were made:

– a roller is a flat multi-link chain with elastic-viscous bindings superimposed on it;

– bindings imposed on the system are holonomic and stationary;

– elastic viscous properties of bindings are represented by Voigt's bodies;

– mass of the links are concentrated in the centers of mass;

– links of the calculation scheme are presented as absolutely rigid;

– external influences are represented by concentrated forces;

– there are no clearances in hinges [13].

The generalized calculation scheme of the dynamic system "Supporting surface–roller–operator" (Fig. 3) is a system with three masses:

– mass m_1 includes the mass of drive rolls, frame and engine. The center of mass of the first link is at point O_1;

– mass m_2 includes the mass of the rear roll, frame, rotating gear, part (25%) of the mass of an operator. The center of mass of the second link is at point O_2;

– mass m_3 includes the mass of a seat, part (75%) of the mass of an operator. The center of mass of the third link is located at the point O_3 [10, 13].

The dynamic system "Supporting surface–roller–operator" is considered in the right inertial coordinate system $O_0X_0Z_0$ associated with a non-deformable base.

The position of the system links in the inertial coordinate system is determined by the following local coordinate systems:

– coordinate system $O_1X_1Z_1$ is connected to the frame of the front vibrating rolls;

– coordinate system $O_2X_2Z_2$ is connected to the rear vibrating roll frame;

– coordinate system $O_3X_3Z_3$ is connected to the operator's seat.

The origin of coordinates coincide with the centers of mass [2, 14].

To describe the movement of links in a dynamic system, the following coordinates are taken:

Z_1 – displacement of the center of mass of point O_1 along axis O_1Z_1;

Z_2 – displacement of the center of mass of point O_2 along axis O_2Z_2;

Z_3 – displacement of the center of mass of point O_3 along axis O_3Z_3 [2].

The elastic-viscous properties of the soil are characterized by stiffness coefficients c_1, c_2 and viscous friction coefficients b_1, b_2. The elastic-viscous properties of the traction system are characterized by stiffness and viscosity coefficients c_4 and b_4. The elastic-viscous properties of the suspension of the operator's seat are characterized by stiffness and viscosity coefficients c_3 and b_3 [15].

In the gravitational field, the masses form gravity shown in the design scheme by vectors $m_i\vec{g}\ (\vec{F}_2, \vec{F}_3, \vec{F}_4)$ [1].

From the motor and vibration exciter side, the driving force acts on the first link

$$\vec{F}_1 = \vec{F}_1' + \vec{F}_2''.$$

From the front rolls, gravity acts on the compacted soil $\vec{F}_2$. The impact of the internal combustion engine, the vibratory roll and the mass of the links on the treated surface leads to the appearance of reactions $\vec{F}_5, \vec{F}_6$. The magnitude of each of these reactions is the sum of two components: static and dynamic [2], i. e.

$$F_5 = F_5^{\text{ст}} + F_5^{\text{д}};\, F_6 = F_6^{\text{ст}} + F_6^{\text{д}}.$$

The static component depends on the gravity of the corresponding part of the roller [1]:

$$F_5^{\text{ст}} = m_1 g F_6^{\text{ст}} = m_2 g + m_3 g.$$

Dynamic components depend on the parameters of the supporting surface and are determined by the formulas [1]

$$F_5^{\text{д}} = -K_1 F_1 F_6^{\text{д}} = -K_2 F_1.$$

The system of equations describing the behavior of an oscillatory dynamic system has the form:

$$\begin{cases} m_1\ddot{Z}_1 + (b_1 + b_4)\dot{Z}_1 + (c_1 + c_4)Z_1 - b_4\dot{Z}_2 - c_4 Z_2 = F_1 + F_2 + F_5; \\ (m_2 + m_3)\ddot{Z}_2 + (b_2 - b_3 - b_4)\dot{Z}_2 + (c_2 - c_3 - c_4)Z_2 - b_4\dot{Z}_1 - c_4 Z_1 + b_3\dot{Z}_3 + C_3 Z_3 = F_6 - F_3 - F_4; \\ m_3\ddot{Z}_3 + b_3\dot{Z}_3 + c_3 Z_3 - b_3\dot{Z}_2 - c_3 Z_2 = F_4. \end{cases}$$

To solve the system of differential equations, we get rid of coefficients of the highest derivative. To do this, we divide the first equation of the system by m_1, the second – $(m_2 + m_3)$, the third – m_3, and as a result we get the canonical system of differential equations [16]:

$$\begin{cases} \ddot{Z}_1 + \dfrac{(b_1 + b_4)}{m_1}\dot{Z}_1 + \dfrac{(c_1 + c_4)}{m_1}Z_1 - \dfrac{b_4}{m_1}\dot{Z}_2 - \dfrac{c_4}{m_1}Z_2 = \dfrac{(F_1 + F_2 + F_5)}{m_1}; \\ \ddot{Z}_2 + \dfrac{(b_2 - b_3 - b_4)}{(m_2 + m_3)}\dot{Z}_2 + \dfrac{(c_2 - c_3 - c_4)}{(m_2 + m_3)}Z_2 - \dfrac{b_4}{(m_2 + m_3)}\dot{Z}_1 - \dfrac{c_4}{(m_2 + m_3)}Z_1 + \dfrac{b_3}{(m_2 + m_3)}\dot{Z}_3 + \dfrac{c_3}{(m_2 + m_3)}Z_3 = \dfrac{(F_6 - F_3 - F_4)}{(m_2 + m_3)}; \\ \ddot{Z}_3 + \dfrac{b_3}{m_3}\dot{Z}_3 + \dfrac{c_3}{m_3}Z_3 - \dfrac{b_3}{m_3}\dot{Z}_2 - \dfrac{c_3}{m_3}Z_2 = \dfrac{F_4}{m_3}. \end{cases}$$

Results

The analytical solution of this system of differential equations is a very difficult task, therefore, the solution of the system of equations was performed by numerical methods [17–19]. The model of the “Supporting surface–roller–operator” system implemented in MathLab, the Simulink extension, is shown in Fig. 4.

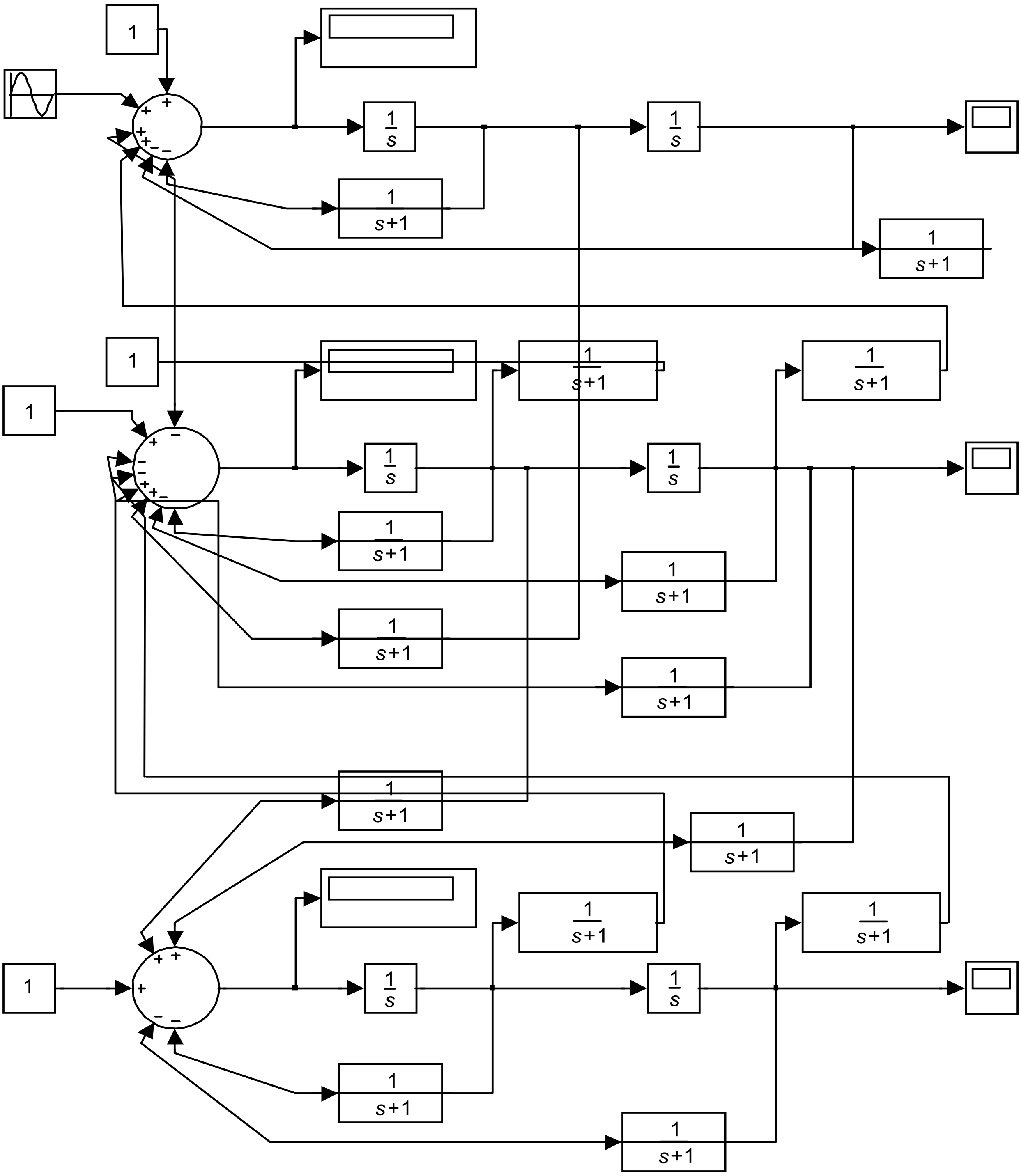

Figure 4. System model “Support surface–roller–operator” implemented in the MathLab, extension of Simulink.
Рисунок 4. Модель системы «Опорная поверхность–каток–оператор», реализованная в MathLab, расширении Simulink.

Discussion and conclusion

Thus, the problem posed by the authors was to compile a mathematical model of a road vibrating roller, which allows us studying the processes occurring in the dynamic system “Supporting surface–roller–operator”. Accordingly, it is advisable to use a mathematical model to solve problems on improving the vibration protection system of a road machine operator. It is also planned to use the mathematical model of the road roller as a basis for creating a robotic complex with an automated control system designed to perform compaction of coatings and foundations during road construction.

CONTRIBUTION OF THE AUTHORS

P. A. Korchagin – academic advising when writing this work, justification and proof of the relevance of the study of this topic, the implementation of the structural diagram of a dynamic system in MathLab (Simulink) in order to determine the optimal design parameters of the road-building machinery.

I. A. Tetherina – analytical review of previous studies, development of a structural diagram of the mathematical model, formation of the reference list and conclusion.

E. A. Korchagina – analysis of the issue, substantiation of the calculation scheme, description of the dynamic system and its individual subsystems, compilation of equations of the mathematical model of the system.

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Математическая модель дорожного катка

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Аннотация

Введение. В качестве объекта исследования рассмотрен процесс уплотнения грунтового основания дорожным вибрационным катком. Основное назначение виброкатков, используемых в дорожном строительстве, – снижение энергоемкости процесса уплотнения и увеличение производительности выполняемых операций. С 1980-х гг. в машиностроительной отрасли отмечена тенденция отказа от производства статических вальцовых катков. Уменьшив амплитуду колебаний или совсем отключив вибратор, можно получить те же статические режимы, а соответственно и результаты укатки. Кроме этого, снижение динамических воздействий положительно сказывается на физическом состоянии оператора строительно-дорожной машины, стабилизирует самочувствие и повышает производительность.

Материалы и методы. Представлена математическая модель динамической системы «Опорная поверхность–каток–оператор». Основные составляющие динамической системы описаны в виде упорядоченных и взаимодействующих между собой подсистем. Определены силы, действующие на динамическую систему и являющиеся источниками динамических воздействий. Отражены расчетные схемы подсистем «Оператор» и «Каток», представляющих наибольший интерес с точки зрения виброзащиты.

Результаты. Результатом проделанной работы можно считать составление обобщенной схемы динамической системы; расчетной схемы динамической системы; математической модели «Опорная поверхность–оператор–каток»; реализацию математической модели в MathLab и его дополнительном пакете расширения Simulink.

Обсуждение и заключение. Представленная математическая модель позволяет проводить исследования процессов, происходящих в динамической системе «Опорная поверхность–каток–оператор». Наиболее рационально математическая модель может быть использована при разработке методов и средств, направленных на совершенствование системы виброзащиты операторов дорожных вальцовых катков. Математическую модель дорожного катка планируется использовать в качестве основы для создания роботизированного комплекса с автоматизированной системой управления, предназначенного для выполнения операций по уплотнению покрытий и оснований при строительстве дорог.

Ключевые слова: строительно-дорожные машины, каток дорожный, математическое моделирование, виброзащитные системы, вибрация.

ВКЛАД АВТОРОВ

П. А. Корчагин – научное руководство при написании работы, обоснование и доказательство актуальности исследования данной тематики, реализация структурной схемы динамической системы в MathLab (Simulink) с целью определения оптимальных параметров конструкции дорожной машины.

И. А. Тетерина – аналитический обзор предыдущих исследований, разработка структурной схемы математической модели, формирование списка литературы и заключения.

Е. А. Корчагина – проведение анализа вопроса, обоснование расчетной схемы, описание динамической системы и отдельных ее подсистем, составление уравнений математической модели системы.

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