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Control algorithm for an elastic-viscoplastic model to study processes of shock interaction of bodies

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Introduction. In engineering practice, dynamic processes, with the help of which mechanics of interaction of machine components and structural elements are described and studied, are of great importance. These dynamic processes are the cause of large deformations leading to the destruction. The research objective is to develop a more accurate shock simulation algorithm through the controlled transformation of the mechanorheological shock process model from elastic-viscous to elastic-viscoplastic.

Materials and Methods. Differential equations of the model movement are proposed. The conditions for the transformation of the model during the transition from elastic to plastic deformations, from the stage of loading the model to the stage of unloading under the shock interaction with the surface, are considered. When calculating deformations, the assumption is made that elastic and plastic deformations occur simultaneously from the very onset of the impact. The model functioning method is considered in detail, the algorithm of the model operation is developed, the logic of its functioning is described in detail.

Results. To study shock processes, a mechanoreological elastic-viscoplastic model was developed. An important parameter of the model is the force corresponding to the onset of plastic deformation. As a result of the research, a more perfect algorithm was created, and a new computer program was developed to study the shock process using an elastic-viscoplastic model with an adjustable elastic-plastic transformation.

Discussion and Conclusions. The results obtained can be used to improve the accuracy and reliability of simulation of shock processes in order to further develop the techniques for determining the physical and mechanical characteristics of materials by shock methods. Knowledge of the mechanical characteristics of materials is required when solving various research problems through mathematical modeling of vibration and shock processes. At the same time, an important task is to adapt the design model to the real shock process, for which it is required to develop appropriate methods and techniques.

Keywords: elastic-viscoplastic model, shock interaction of bodies, mathematical modeling of shock process.

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Introduction. In engineering practice, dynamic processes (shock, vibration) are critical. They are used to describe and study the mechanics of interaction of machine parts and structural elements. At the same time, much attention is paid to the shock process since, in this case, the bodies are exposed to high dynamic loads. They can cause large deformations and damage to equipment. These circumstances explain the increased attention of scientists and engineers to modeling and research of dynamic processes [1–14]. The development of express methods and techniques for determining the physical and mechanical characteristics of materials by shock methods is of particular practical interest. At the same time, a crucial task is to adapt the computational model to the real shock process. In this regard, the study objective is to create a more accurate algorithm for modeling a shock process due to the controlled transformation of the mechanorheological model of the shock process from elastic-viscous to elastic-viscoplastic. The developed algorithm allows for the transformation of the model at the loading stage based on the specified conditions, which provides a better and more reliable simulation of the shock process, taking into account the real plasticity of the material. The previous development did not allow this transformation to be carried out, and the model under the impact interaction was elastic-viscoplastic from the very beginning of loading.

Materials and Methods. One of the areas of scientific research at Irkutsk National Research Technical University is the modeling and study of the processes of dynamic interaction of solids. To study the dynamics of these processes in order to solve practical problems, an elastic-viscoplastic model was developed and studied [15]. The model is constructed using the rheological and inertial elements m_1 and m_2, combined in two blocks (Fig. 1). One of the blocks is elastic-viscous K_1–C. It is designed to simulate elastic deformations of the body. They arise under the impact of an external load and disappear in its absence. The elastic-plastic block K_2–f_2 simulates the plastic deformations remaining after the load is removed. The mass of the body is taken into account by the inertia element m_1. The mass m_2 is introduced to describe the motion dynamics of an elastic-viscoplastic model using two second-order differential equations. To exclude the influence of m_2 on the dynamics of the process, its value was assumed to be small ($m_2 \le 0{,}001\, m_1$). As the calculations showed, under this condition, you can accept $N_1 \approx N_2$ (4).

Consider the shock process on the example of a spherical body. When a body is loaded, internal forces arise in it that prevent changes in the shape and size of the body, that is, prevent (2) its deformation. One of them is the elastic resistance force. In this case, additional deformation resistances, which are called viscous, may occur. They are related to the rate of deformation of the body. On the model, the data of the resistance to deformation of the body is described by the expressions:

$$
\begin{aligned}
&N_1 = F_V + F_{E1},\\
&F_V = C(\dot{y}_1 - \dot{y}_2)^{s1}(y_1 - y_2)^{s2},\\
&F_{E1} = K_1(\,y_1 - y_2\,)^{n1}.
\end{aligned}
\tag{1}
$$

where $y_1, y_2, \dot{y}_1, \dot{y}_2$ — dynamic characteristics of the model describing the movement and velocity of the inertial elements m_1 and m_2; K_1 — the model parameter, which characterizes the elastic properties of the material (elastic-viscous block of the model); C — the model parameter, which characterizes the viscous (dissipative) properties of the material in the same block of the model (3).

The deformation resistance forces that occur in the elastic-plastic block of the model are described by the following expressions:

$$
\begin{aligned}
&N_2 = F_P + F_{E2}; N_2 \approx N_1;\\
&F_{E2} = K_2\, y_2^{\,n2};\\
&F_P = f_2\, y_2^{\,n3} + F_{ST}.
\end{aligned}
\tag{2}
$$

Here, F_{ST} — the loading force of the model, under which the elastic-plastic block of the model starts to work, taking into account the plastic deformations of the material; K_2 — the model parameter that characterizes the elastic properties of the material under plastic deformation (elastic-plastic block of the model); f_2 — the model parameter that characterizes the plasticity of the material in the same block of the model (3).

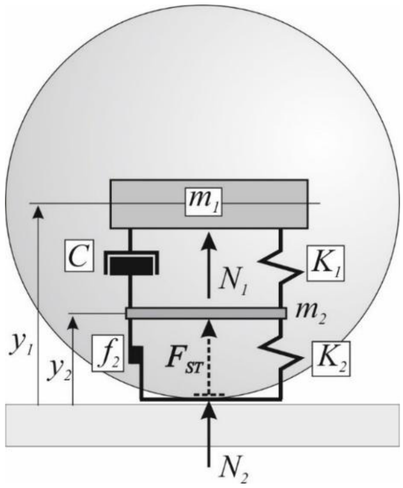

Fig. 1. Elastic-viscoplastic mechanorheological model

The variables $y_1, \dot{y}_1$ describe the amount and rate of total deformation. The variables $y_2, \dot{y}_2$ describe the amount and rate of plastic deformation. Hence, the rate and amount of elastic deformation is specified as $\dot{y}_1 - \dot{y}_2;\ y_1 - y_2$.

The rheological elements of the model (elastic, viscous, plastic) have nonlinear characteristics, that is, elastic, viscous, and plastic resistances of deformation are proportional to the rate and amount of deformation to a given degree (s_1, s_2, n_1, n_2, n_3). As a recommendation, it can be noted that for elastic resistances upon impact of a spherical body, $n_1 = n_2 = 3/2$ [2–4] should be used, for viscous and plastic resistances, a value equal to one can be taken [2, 3].

Research Results. Consider how the model works. At the initial stage of using the model in scientific research, a simplified version of its functioning was used. It was assumed that under the deformation of the body, elastic and plastic deformations occur simultaneously from the very beginning of loading. This allowed us to develop and test in practice a simpler algorithm for the model functioning. On its basis, a research computer program[1], was developed, a complex of scientific studies of the shock process was carried out on the model[2], including those presented in paper [16].

However, this simplification limits the capabilities of the model and does not allow to fully perform studies of shock processes. Therefore, as a result of further research, a more advanced algorithm was created, and a new computer program was developed to study the shock process using an elastic-viscoplastic model with an adjustable elastic-plastic transformation[3]. Consider this algorithm of the model functioning in greater detail.

The developed algorithm provides the following sequence of functioning of the model blocks. At the initial stage of the shock process, only the elastic-viscous block of the model K_1–C is involved in the operation. It enables to calculate the elastic deformations of the body at the loading stage (Fig. 2). In this case, the elastic-plastic block of the model does not function, since up to a certain point, plastic deformations in the body may be absent. The appearance of plastic deformations corresponds to the specified force F_{ST}. When the calculated loading force N_1 reaches the set value ($N_1 = F_{ST}$), the elastic-viscous model is converted to an elastic-viscoplastic mode. The elastic-plastic block of the model starts to function. When the loading force reaches its maximum value N_{max}, the growth of deformation stops, and the loading stage ends. Due to the material elasticity, the body starts to restore its original shape and size, and the stage of unloading the model comes. During this process, elastic deformations disappear, while the resulting plastic deformations remain in the body and, accordingly, on the model. Thus, at the stage of unloading the model, only the elastic-viscous block works.

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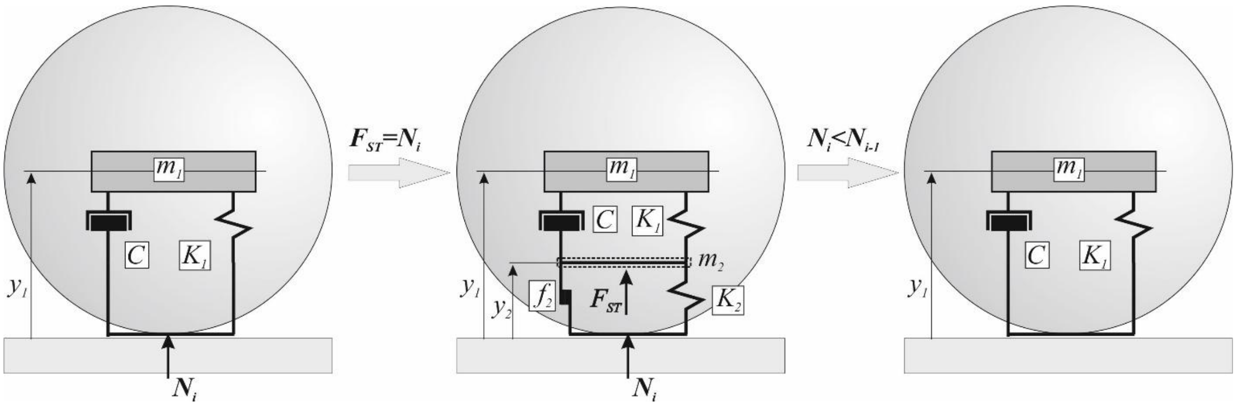

Fig. 2. Model transformation diagram

The contact interaction stage ends when the normal reaction force N, defined by equations (1) and (2), becomes zero. The body bounces off the surface to a height of h.

The process of loading the model at various stages of deformation is described using differential equations, which are given below:

$$m_1 \ddot{y}_1 + C_1 \dot{y}_1^{s1} y_1^{s2} + K_1 y_1^{n1} = -m_1 g, \tag{3}$$

$$m_1 \ddot{y}_1 + C_1 (\dot{y}_1 - \dot{y}_2)^{s1} (y_1 - y_2)^{s2} + K_1 (y_1 - y_2)^{n1} = -m_1 g, \tag{4}$$

$$m_2 \ddot{y}_2 + K_2 y_2^{n2} + f_2 y_2^{n3} + C_1 (\dot{y}_2 - \dot{y}_1)^{s1} (y_2 - y_1)^{s2} + K_1 (y_2 - y_1)^{n1} = -m_2 g + F_{ST}. \tag{5}$$

The elastic deformations of the model at the loading and unloading stages are calculated using equation (3). Using equations (4) and (5), the elastic and plastic deformations of the model are calculated when it is loaded at the stage of plastic deformation of the material.

The strength of the normal reaction at the elastic deformation stage is determined from the formula:

$$N_i = C \dot{y}_1^{s1} y_1^{s2} + K_1 y_1^{n1}. \tag{6}$$

The normal reaction force at the stage of plastic deformation is determined from the formula:

$$N_i = K_2 y_2^{n2} + f_2 y_2^{n3} + F_{ST}. \tag{7}$$

The calculation is performed with the specified time step dt. The impact time is determined from the formula:

$$T = dt \cdot i, \tag{8}$$

where i — the number of steps.

The condition for the transition from elastic to plastic deformation has the form:

$$N_i > F_{ST} \tag{9}$$

The condition for the end of the loading stage and the beginning of the unloading stage of the model:

$$N_{i-1} > N_i \tag{10}$$

The condition for the end of the contact interaction stage of the model:

$$N_i = 0 \tag{11}$$

Consider the algorithm for studying the shock process (Fig. 3).

1. Block 1 forms the initial data of the process under study.

2. Block 2 enters the initial data of the process: the initial impact time $t = 0$, the initial deformation of the body (models) $y = 0$, the initial rate of the deformation $\dot{y} = \dot{y}_s$, the initial impact force $N = 0$.

3. Block 3 calculates the values of the coefficients of the model K_1, K_2, f_2, C.

4. Block 4 calculates the impact time and records the number of calculation steps at the loading stage under elastic deformation.

5. Block 5 calculates the parameters of the impact interaction of bodies using the elastic-viscous block of the model. The elastic deformation y_1 and the deformation rate are calculated (equation (3)). The impact force N_i is determined (equation (6)).

6. Blocks 6 and 16 perform the check according to condition (11). If the condition is not met, the calculation continues at the next step of the shock interaction stage. If the condition is met, then the calculation is completed, and the transition to the rebound stage of the model is performed.

7. Blocks 7 and 12 control the moment of completion of the loading process of the model. The fulfillment of condition (10) means that the loading stage of the model has completed, and the force of the contact interaction N_i starts to decrease. The calculation is performed at the stage of the model unloading. The calculation is passed to block 4 or 14. If condition (10) is not met, the contact force N_i continues to increase. The loading stage of the model continues, and the calculation is performed by blocks 8 or 13.

8. Block 8 records the largest value of the contact force N_{max}, the corresponding time in the process of impact T_{Nmax} and transmits control to block 9.

9. Block 9 determines the end of the elastic deformation stage when the model is loaded. If condition (9) is satisfied, it means that the force of the normal reaction of the model N_i exceeds the specified force F_{st}, corresponding to the beginning of the formation of plastic deformations. The elastic deformation stage is completed, the elastic-plastic deformation stage begins, and control is transferred to unit 10. If condition (9) is not met, it means that the normal reaction force of the model N_i is less than the set value F_{st}, and there are no plastic deformations. The calculation is transferred to block 4 to perform the calculation in the next step of the elastic deformation stage.

10. Block 10 calculates the current time and the number of the calculation step at the elastic-plastic deformation stage.

11. Block 11 calculates the parameters of the process of impact interaction of bodies at the stage of plastic deformation. Deformation rates and amount of the model $y_1, \dot{y}_1, y_2, \dot{y}_2$ are calculated (equations (4) and (5)), and the contact interaction force N_i is determined (equation (7)). Then the control is transferred to block 12.

12. Block 12 determines the end of the loading stage of the model. If condition (10) is satisfied, it means that the normal reaction force N_i decreases, the loading stage of the model is over, and the transition to the unloading stage of the model is performed. Control is transferred to block 14. If condition (10) is not met, it means that the force of the normal reaction N_i continues to increase, the loading stage of the model is in progress, and control is transferred to the block 13.

13. Block 13 records the largest value of the contact force N_{max} and the corresponding time in the process of impact T_{Nmax}, and transmits control to block 10 for calculation at the next step of the elastic-plastic deformation stage.

14. Block 14 calculates the current time and the number of the calculation step at the elastic deformation stage when unloading the model. Control is transferred to block 15.

15. Block 15 calculates the parameters of the process of impact interaction of bodies using an elastic-viscous model under unloading: elastic deformation y_1, deformation rate $\dot{y}_1$ according to equation (3), normal reaction force N_i according to equation (6). Control is transferred to block 16.

16. Block 16 checks condition (11). If the condition is not met, the impact interaction stage continues, and control is transferred to unit 14. If the condition is met, the calculation at the impact interaction stage is completed, and the transition to the model rebound stage is performed. Control is transferred to block 17.

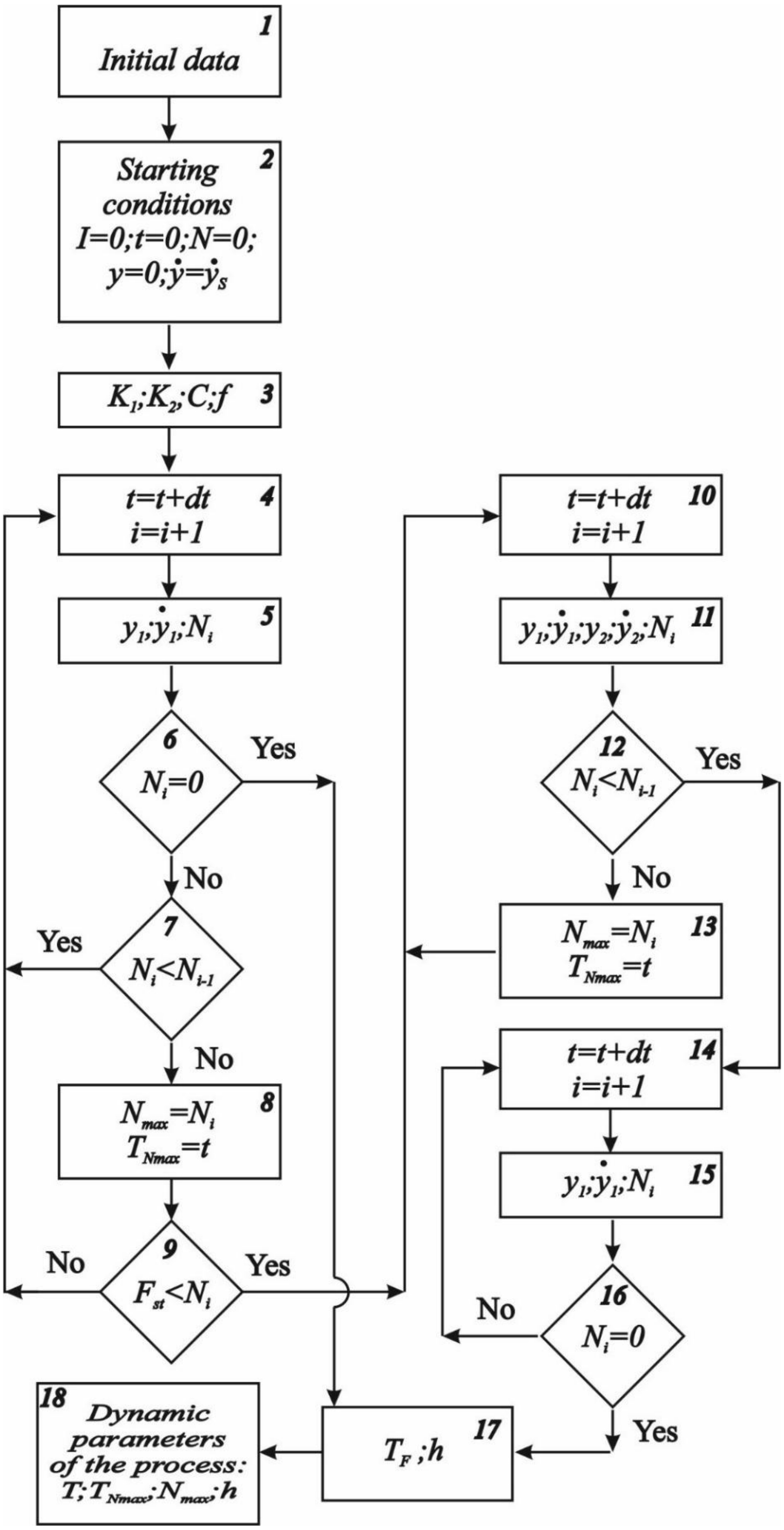

Fig. 3. Algorithm diagram

17. Block 17 determines the height of the body bounce h, the bounce flight time T_F, and transfers control to block 18.

18. Block 18 generates and outputs the main characteristics of the shock process: the time of the impact interaction of bodies (model) T (equation (8)); the force of the impact interaction of bodies N_{max}; the time in the process of impact T_{Nmax}, corresponding to N_{max}; the body rebound height (model) h.

On the basis of the created algorithm, a research computer program[4] has been developed. The author's program was used to study the process of impact interaction of bodies [17]. The effect of various factors on the dynamics of the shock process was investigated. In particular, the influence of the mechanical properties of the material (elasticity, viscosity, plasticity) on the time and force of the impact interaction of a spherical body with the surface, the amount and rate of deformation, and the rebound height after impact, was studied on the model. At the same time, various options of the elastic-plastic transformation of the research model reflecting the transition from the elastic to the elastic-plastic state of the material under loading were considered

Let us compare the operation of the elastic-viscoplastic model according to the previous algorithm (Graph 1, Fig. 4) and the new one (Graph 2, Fig. 4).

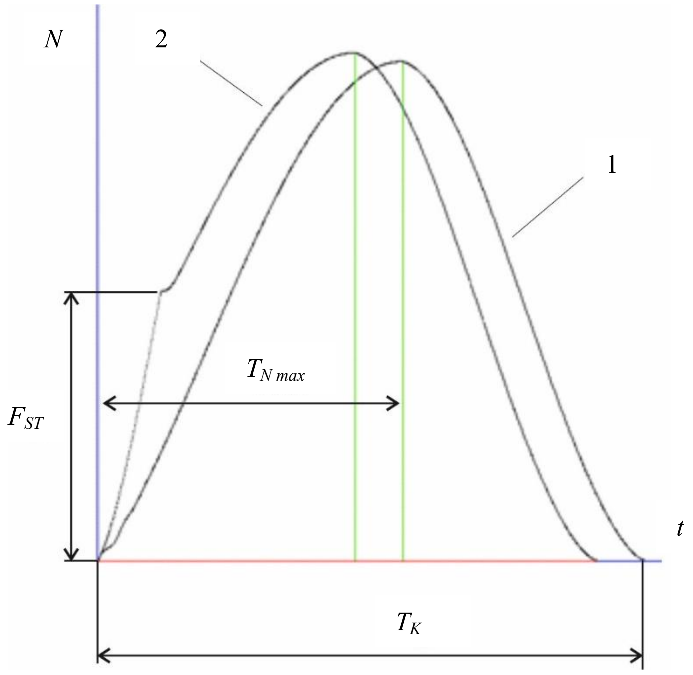

Fig. 4. Change in the force of the impact interaction of bodies *N*

When modeling the shock process of the interaction of bodies, the new algorithm provides the transition from the elastic-viscous model to the elastic-viscoplastic model for a given force of the impact interaction F_{ST}. This transition to the model corresponds to the beginning of the formation of plastic deformations in the material, which makes it possible to describe the shock process more reliably and accurately

It is clearly seen that the regularity of the change in the strength of the normal reaction calculated by the new algorithm (Graph 2, Fig. 4) differs significantly from a similar pattern (Graph 1, Fig. 4) obtained on the previous version of the algorithm. The impact time T_K and the time from the beginning of the impact to the maximum of the impact force T_{Nmax} differ (Fig. 4). The value N_{max} can also change significantly. Thus, the developed algorithm provides a better solution to the problems of adapting the elastic-viscoplastic model to the real processes of impact interaction of bodies taking into account their mechanical properties.

Conclusion. As a result of the research, a more advanced algorithm has been created and a new computer program has been developed to study the shock process using an elastic-viscoplastic model with an adjustable elastic-plastic transformation. The differential equations of model motion are presented. The conditions for the model transformation under the transition from elastic to plastic deformations, from the loading stage of the model to the unloading stage in the process of the impact interaction with the surface are considered. The methodology of the model functioning is considered in detail, the algorithm of the model operation is compiled, the logic of its functioning is described in detail.

The advantage of the new algorithm is that it provides a more accurate description of the process at the moment of the onset of the formation of plastic deformations in the material when it is loaded. The moment of the onset of plastic deformations on the model can be precisely set and fully correspond to the actual behavior of the material. For this, for example, data from experimental studies of the shock process can be used. This feature was not available in previous versions of the algorithm and the program.

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So, for example, to study the shock process of interaction of a spherical body and a surface, an algorithm for adapting the elastic-viscoplastic model to the conditions of the shock process of interaction of bodies[5] was developed.

In this algorithm, a condition was implemented under which elastic and plastic deformations occur simultaneously from the very beginning of the impact interaction. However, this simplification of the real process limits the possibilities of modeling, especially when studying the effect of material plasticity on the dynamics of the shock process.

The improved algorithm enables to implement the capabilities of the elastic-viscoplastic model in full. The elastic-plastic transformation of the model can be performed according to a given plan, which will provide a better adaptation of the model to the real shock process. At the same time, the actual plastic deformations can be simulated more reliably.

Thus, the new parameter of the model F_{ST} (the loading force corresponding to the appearance of plastic deformations in the material), introduced through the developed algorithm, expands the possibilities of adapting the model to real shock processes and increases the accuracy of the model in describing plastic deformations. The algorithm performance was validated in the course of studies of the shock process using the model [18].

Practical application of the developed program can significantly improve the accuracy and reliability of modeling shock processes. In particular, the results of studies on shock processes can be used for improving methods and techniques for evaluating the mechanical properties of structural materials based on the shock principle of action. Thus, using the previous version of the algorithm, a new method for determining the elastic modulus of a material has been developed, based on the impact interaction of bodies [16]. Knowledge of the mechanical properties of materials is required when performing research to form mathematical models of the processes of vibration and shock interaction of mechanical systems. At the same time, to adapt the computational model to the real shock process, which requires the development of appropriate methods and techniques, is a challenge. The solution to these problems is possible on the basis of the obtained research results.

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Claimed contributorship

V. L. Lapshin: development of the logic and mechanics of the model functioning; determination of the research objectives and tasks; development of an algorithm for computer modeling of the impact process; formulation of conclusions. E. V. Zenkov: development of a mathematical model; development of a new block of a computer program; writing the paper.

All authors have read and approved the final manuscript.