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Improving the Models of Dynamics of Adaptively Controlled Elements and Drives Based on Functional Materials

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The investigation of thermo-mechanical processes in materials and elements with shape memory effect (SME) and the simulation of dynamics of elements and drives based on alloys with shape memory and taking into account the adaptation properties of material are carried out in order to develop adaptive-controlled thermomechanical drives or actuators, heat regulator and automation tools of technological processes. The effect of the thermal cycling modes and the magnitude of deformation, which induces the shape memory effect, on the level of reversibility of the deformation, the implementation of the effect of reversible shape memory, the magnitude of the excited force, and the recoverable deformation are investigated. A generalized dynamic model of a technical mechanism based on the elements with SME is developed. The model formally describes adaptive control of mechanism, based on which, the adaptation algorithms can be synthesized. The developed models can be used in the calculation and design of various thermomechanical drives and actuators, heat regulators, thermal compensators and damping devices based on elements from shape memory alloys, as well as in a synthesis of adaptive control algorithms of continuous and discrete classes in the terminal control, homing guidance and stabilization modes.

Key words: shape memory effect, martensitic transformation, modelling, deformation-force characteristics, thermomechanical actuator, adaptive control.

Проведено дослідження термомеханічних процесів у матеріалах і елемен-

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тах з ефектом пам'яті форми (ЕПФ) і моделювання динаміки елементів і приводів на основі стопів з пам'яттю форми з урахуванням адаптаційних властивостей з метою створення адаптивно-керованих термомеханічних двигунів чи приводів, терморегуляторів і засобів автоматизації технологічних процесів. Досліджено вплив режимів термоциклування і величини деформації наведення ЕПФ на ступінь оборотності деформації, реалізацію ефекту оборотної пам'яті форми, величини зусилля, що збуджується, і відновлюваної деформації. Побудовано узагальнену динамічну модель технічного засобу на основі термосилових елементів з ЕПФ, що формалізовано описує його адаптивне управління, на основі якої можуть бути синтезовані алгоритми адаптації. Розроблені моделі можуть бути використані при розрахунку і проектуванні різних термомеханічних двигунів і приводів, терморегуляторів, термокомпенсаторів і демпфуючих пристроїв на основі елементів зі стопів з ЕПФ і при синтезі алгоритмів адаптивного управління неперервного і дискретного класу в режимах термінального управління, самонаведення і стабілізації.

Ключові слова: ефект пам'яті форми, мартенситне перетворення, моделювання, деформаційно-силові характеристики, термомеханічний привід, адаптивне управління.

Проведено исследование термомеханических процессов в материалах и элементах с эффектом памяти формы (ЭПФ) и моделирование динамики элементов и приводов на основе сплавов с памятью формы с учётом адаптационных свойств с целью создания адаптивно-управляемых термомеханических двигателей или приводов, терморегуляторов и средств автоматизации технологических процессов. Исследовано влияние режимов термоциклирования и величины деформации наведения ЭПФ на степень обратимости деформации, реализацию эффекта обратимой памяти формы, величины возбуждаемого усилия и восстанавливаемой деформации. Построена обобщённая динамическая модель технического средства на основе термосиловых элементов с ЭПФ, формализовано описывающая его адаптивное управление, на основе которой могут быть синтезированы алгоритмы адаптации. Разработанные модели могут быть использованы при расчёте и проектировании различных термомеханических двигателей и приводов, терморегуляторов, термокомпенсаторов и демпфирующих устройств на основе элементов из сплавов с ЭПФ и при синтезе алгоритмов адаптивного управления непрерывного и дискретного класса в режимах терминального управления, самонаведения и стабилизации.

Ключевые слова: эффект памяти формы, мартенситное превращение, моделирование, деформационно-силовые характеристики, термомеханический привод, адаптивное управление.

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1. INTRODUCTION

The use of new functional materials with shape memory effect (SME) as thermo-mechanical drives (TMD), actuators as well as heat regulators, temperature compensators and damping elements, has significant advantages compared with traditional mechanisms and also provides various opportunities for creating adjustable and adaptive systems [1–5].

Based on the empirical evidence of worldwide research in using materials with SME, technological methods of their processing in conjunction with the operational capabilities has supported the hypothesis of the need for thermal-force cycling in the pre-deformation state to be developed [6–8].

An experimental test using the example of titanium nickelide of VSP-1 grade, confirms the correctness of the hypothesis. As a result of research, a method for the manufacture of products made from shape memory alloys (SMA) has been proposed. This method is based on a special thermal cycling and annealing mode, which provides a reversible shape memory effect and stabilization of thermomechanical characteristics (details can be found in [9]). At the same time, a certain combination of the magnitudes of deformations of guidance and phase plasticity, temperature ranges of annealing and structural transformations of the crystal lattice allows improving operational properties and expanding technological capabilities (enhancing the SME, providing reversible SME, increasing the generated stresses and magnitudes of the reinstate deformation, reducing the stress of guidance) of elements made from SMA.

Analysis of previous research publications shows that modelling of the dynamics of adaptively controlled elements was developed only in general form [10–15], without taking into consideration the specifics and characteristics of elements with SME, as well as the thermomechanical and especially thermoelectric characteristics [16, 17] of materials with SME are insufficiently investigated. There is practically no analysis of ways to increase the efficiency of TMD. The algorithms and modes of adaptive control of technological elements from materials with SME are not analysed and unfounded. This article deals with the solution of these important issues.

2. MAIN PART

Obtained calculating methods [17] allow us to determine geometrical and deformative-force parameters of thermosensitive elements (TSE), which are used immediately after the final thermal-treatment in a single acting mechanism of the technological systems. Subsequent TSE thermal cycling over the range of the phase transformation is accompanied at the initial stage by the gradual deformation accumulation in the direction of the applied stress (because of no closuring thermomechanical hysteresis). It can be explained by the fact that other channels of deformation are simultaneously initiated with the conversion of the material ductility when the stress is higher than yield of strength of the phase. These deformation channels are determined by the development of accommodative shifts, non-isothermal creep and dislocation plasticity.

Besides, it's possible to observe that a phase and material strain hardening increase dislocation yield strength and the degree of deformation reversibility. Non-isothermal creep rate decreases and stabilizes. Texturing martensite occurs. It means emergence and growth of the crystallographic options that provide the greatest TSE forming in the direction of the applied load. Forming of the naturally inherited defect structures (such as dislocation) leads to the specific transformation of metal lattice when the direct and inverse transformation is implemented as to the 'exactly back and forth' principle. As a rule defect structure arising due to thermo-force cycling (TFC) is sharply anisotropic and fields of microstressing locally oriented in space are formed and their effect on the martensitic transformation is similar to the external load. As a result TSE get the ability to accumulate deformation intensively at the half-cycle cooling period even in the absence of external load.

In the case of application of TSE in the thermopower drives schemes of cyclic and nonstop motion the final thermomechanical treatment in the form of stabilizing TFC should be implemented. On the basis of experimental data approximating dependences allowing to estimate the changes in the deformation-force characteristics of spring TSE made from TiNi were obtain in the process of thermo-cycling dependence on the number of cycles and guidance deformation.

Changing the maximum guidance stress during deformation in martensitic state described by the dependence of the following form:

$$\overline{\tau_{\text{н}}} = u_0(\gamma_{\text{н}}) + u_1(\gamma_{\text{н}})N^{u_2(\gamma_{\text{н}})},$$

where $\overline{\tau_{\text{н}}} = \dfrac{\tau_N}{\tau_{N=0}}$, τ_N and $\tau_{N=0}$—maxima of guidance stresses after N cycles and without TFC, correspondingly, $u_0(\gamma_{\text{H}})$, $u_1(\gamma_{\text{H}})$, $u_2(\gamma_{\text{H}})$—linear functions of the guidance deformation γ_{H}

$$u_i(\gamma_{\text{н}}) = \begin{cases} A_i\gamma_{\text{н}} + B_i & \text{when } \gamma_{\text{н}} \le \gamma_{\text{ul}}, \\ C_i\gamma_{\text{н}} + D_i & \text{when } \gamma_{\text{н}} \ge \gamma_{\text{ul}}, \end{cases}$$

A_i, B_i, C_i, D_i—constants characterizing the cyclic properties of the alloy and determined from the experimental data (the values of the constants A_i, B_i, C_i, D_i for spring VSP-1 alloy TSE are listed in Table 1), γ_{ul}—ultimate full shape recovery deformation, N—number of thermalcycles (see Fig. 1, *a*).

TABLE 1. The material parameters of the spring TSE (alloy VSP-1).

$u_i(\gamma_H)$		u_0	u_1	u_2
$\overline{\tau_н}$	A_i	3.404	−3.404	−0.649
	B_i	$2.336 \cdot 10^{-4}$	1.003	−0.222
	C_i	−5.003	5.084	3.524
	D_i	0.586	0.411	−0.512
$\overline{\tau'_н}$	A_i	−1.859	2.794	−0.481
	B_i	0.659	0.255	0.021
$\overline{\tau_p}$	A_i	0.124	−0.128	−0.031
	B_i	0.965	0.036	−0.028
γ_{res}	A_i	0.226	−0.226	0.049
	B_i	$5.466 \cdot 10^{-3}$	$-5.314 \cdot 10^{-3}$	−0.035
γ_{rev}	A_i	0.43	−0,446	−0.302
	B_i	$-2.188 \cdot 10^{-3}$	$2.588 \cdot 10^{-3}$	−0.016

Standard deviation of the experimental data from calculated data, defined by the equation for $\overline{\tau_н}$, does not exceed 2.4%.

Changing the maximum guidance stress during the deformation in the range of martensitic transformation (when implementing the transformation plasticity effect (TPE)) is approximated by an exponential dependence of the form:

$$\overline{\tau'_н} = u_0(\gamma_н) + u_1(\gamma_н)\exp\left[u_2(\gamma_н)N\right],$$

where $\overline{\tau'_н} = \dfrac{\tau_N}{\tau_{N=0}}$, $u_i(\gamma_н) = A_i\gamma_н + B_i$.

Standard deviation of the experimental data from calculated data, defined by the equation for $\overline{\tau'_н}$, does not exceed 2.5% (see Fig. 1, *b*).

Changing the maximum reactive stress (implementation of SME) also occurs on an exponential function (see Fig. 1, *c*):

$$\overline{\tau_p} = u_0(\gamma_н) + u_1(\gamma_н)\exp\left[u_2(\gamma_н)N\right],$$

where $\overline{\tau_p} = \dfrac{\tau_p}{\tau_{pN=0}}$, τ_p and $\tau_{pN=0}$—maxima of reactive stresses after N cycles and without TFC, respectively, $u_i(\gamma_н) = A_i\gamma_н + B_i$.

Standard deviation of the experimental data from calculated data, defined by the equation $\overline{\tau_p} = \varphi(N, \gamma_н)$, less than 1.5%.

Effect of TFC and the guidance strain on total residual deformation γ_{res} and reversible deformation γ_{rev} (accumulates in the implementation of reversible SME) can be described by the same exponential dependences. Corresponding surfaces $\gamma_{res} = \varphi(N, \gamma_{н})$ and $\gamma_{rev} = \varphi'(N, \gamma_{н})$ are presented in Fig. 2, *a*, *b* and have standard deviation from the experimental data less than 2%.

The study results of thermoelectric processes in the TSE can be found in [16].

To solve the tasks assigned to the mechanisms and devices, it is necessary to provide targeted movements, speeds and accelerations dictated by the process being implemented. In other words, to ensure the process is correctly undertaken, it is necessary to build program actions (PA) and processes, and then ensure that the PA is controlled so that the transient processes satisfies the specified requirements for accuracy, speed, *etc*. Adaptive control is based on the principles of feedback and self-regulation of the control law PA.

For a formal description of adaptive control, the authors consider a generalized dynamic model of a technical device, which includes a system of dynamic equations describing controlled motions and parameters of elements and devices included in its composition, as well as a system of structural constraints and external conditions. In the gen-

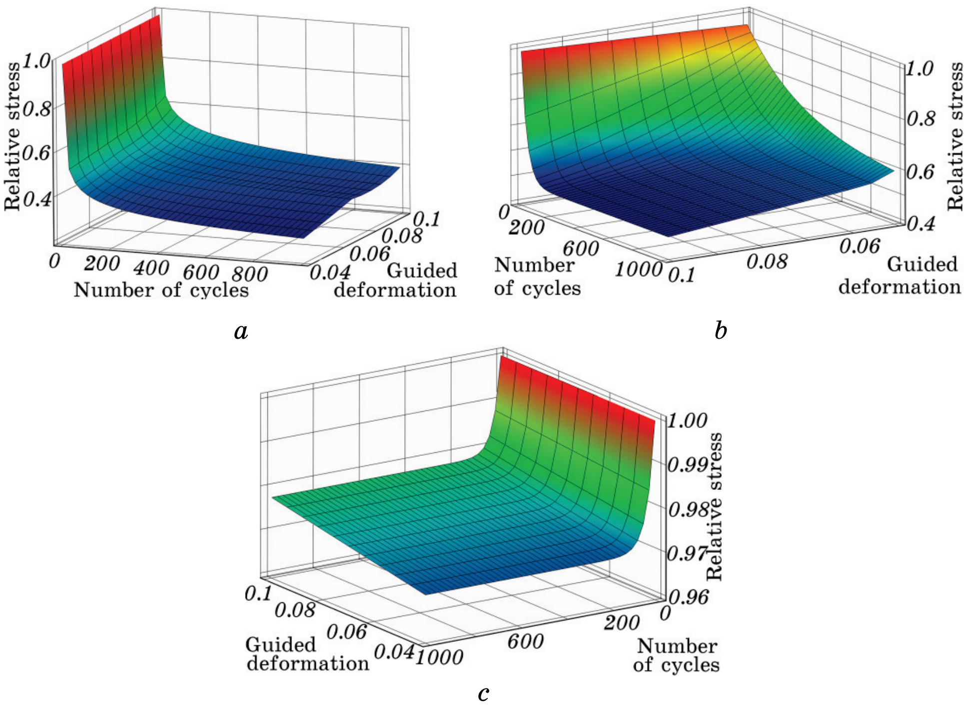

Fig. 1. Changing the maximum strain guidance stresses and reactive stresses when TFC of the TSE: *a*—deformation guidance in the martensitic state, *b*—deformation guidance in the implementation of the TPE, *c*—reactive stresses.

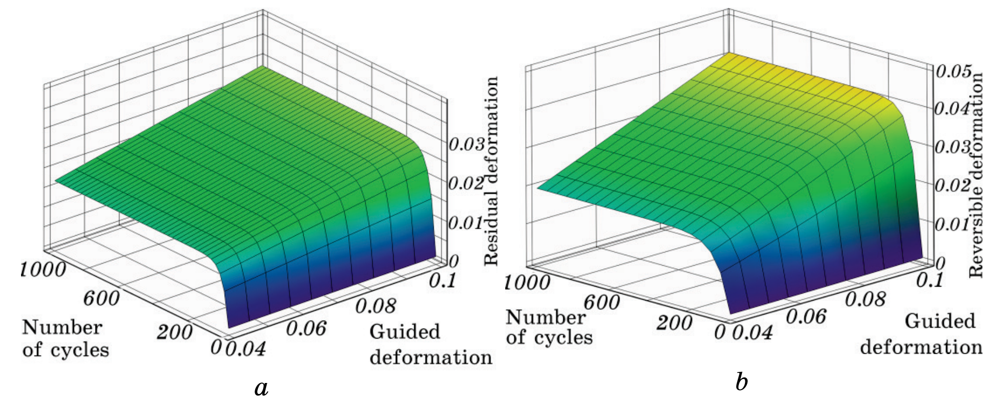

Fig. 2. Changing total TSE deformations during TFC: *a*—the residual deformation, *b*—reversible deformation.

eral case, this is a system of dynamic equations in the form of a vector differential equation [18]:

$$\dot{x} = F(x, u, \xi) + \pi(t), \;\; t \in \left[t_0, t_T\right], \tag{1}$$

where $x = x(t)$ is the n-dimensional state vector of the object, $u = u(t)$—m-dimensional vector of controls supplied to the drives and executive bodies, $\xi = \xi\ (t)$—p-dimensional vector parameters of actuators and drives, $\pi(t)$—n-dimensional vector of external disturbances, t is time, F is a given n-dimensional vector-function depending on the structural features of the object.

The variables x, u, π and parameters ξ have the meaning of real physical variables and parameters describing the functioning of the object. In the case of electromechanical actuators and elements with the SME, the number of components of the state vector x includes controlled coordinates of the actuators and elements, currents in the thermomechanical elements, as well as their first derivatives with respect to time; the number of components of the control vector u are the control voltages produced by the control system and supplied to the actuators; the number of components of the parameter vector ξ is the mass-inertial characteristics of the elements of the actuators and elements, the coefficients of friction and elasticity in the transmission mechanisms, the parameters of the executive-power elements.

To accept the system of equations as illustrated in (1) as a generalized dynamic model of a drive with elements based on the SME, let us characterize the range of the function F and specify the class of constantly acting external disturbances π. The range of definition of the function F, which defines the structure and properties of the equations of dynamics (1), is the set of possible values of the variables x and u and parameters ξ. The boundaries of this range are determined by the structural constraints of the form for all $t \in [t_0, t_T]$:

$$x(t) \in Q_x, \; u(t) \in Q_u, \; \xi(t) \in Q_\xi, \tag{2}$$

where Q_x, Q_u, Q_ξ are given sets in the spectrum of states, controls and parameters, respectively.

External permanent disturbances π are always limited in practice. Formally, this means that

$$\pi(t) \in Q_\pi, \text{ for all } t \in [t_0, t_T], \tag{3}$$

where Q_π is the range of possible values of external disturbances.

An admissible control is any law of variation of control effects $u(t)$ that satisfies the constraint (2). The controlled movements of the object are the solution of the system of differential equation of dynamics (1) for a given admissible control. From a formal point of view, the real movement of an object is described by a vector function:

$$x(t) = X(t, t_0, x_0, u, \xi, \pi),$$

where x_0 is the state of the object at the initial time t_0.

If this motion satisfies the constraint on the state (2), then it is admissible.

For a given PA, the goal of controlling an object is usually reduced to the actual implementation of a PA due to the synthesis of the corresponding admissible control law. The system of equations for the dynamics of an object is solvable with respect to control on some subset

$$P_F(\xi) = \{(x, F(x, u, \xi)) : x \in Q_x, u \in Q_u\},$$

which is subspace controllability. Based on this, equations (1) can be re-written in a more convenient form, in terms of analytical design of control laws:

$$u = U(x, \dot{x} - \pi, \xi), \; (x, \dot{x} - \pi) \in P_F, \; t \geq t_0. \tag{4}$$

Here, U is the control operator defined on the sets P_F and Q_ξ with magnitudes in Q_u and satisfying the ratio $z = F(x, U(x, z, \xi), \xi)$ for all (x, z) of P_F and all ξ of Q_ξ.

The constraint system (2) creates constraints on the rate of change of the state vector

$$\dot{x}(t) \in Q_{\dot{x}} \text{ for all } t \in [t_0, t_T], \tag{5}$$

where $Q_{\dot{x}}$ is a set defined by given sets Q_x, Q_u, Q_ξ, Q_π. Therefore, in the system of constraints (2) the second can be replaced by (5).

The new system of constraints (2), (5), (3) in combination with the equation of object dynamics (1) in the form allowed by control (4) is a generalized dynamic model of the object based on the elements with SME and can be used to synthesize the laws of adaptive control taking into consideration the dynamic characteristics of the object. It follows from the properties of the model that the PA $x_p(t)$ should satisfy the constraints (2) and (5).

The task of the programmed control is to synthesize such a control law that ensures the exact implementation or stabilization of a given PA $x_p(t)$. Knowing $x_p(t)$, it is easy to find a programmable control as a function of time. For this, in the equation (1), we need to put $\pi(t) = 0$ and make the substitution $x = x_p(t)$, $\dot{x} = \dot{x}_p(t)$. As a result, we obtain an equation for the definition of a programmable control $u_p(t)$.

To find an expression for it in an analytical form, we use the property of solvability of the equation of dynamics (1) with respect to the control on a subspace. Then, taking into consideration (4), we obtain the following explicit formula for calculating the programmed control directly from the PA:

$$u(x_p, \xi) = U(x_p, \dot{x}_p, \xi). \tag{6}$$

The coincidence of real movement $x(t)$ and PA $x_p(t)$ is possible only if very harsh conditions are met. The first is the absence of uncontrollable disturbances $\pi(t)$. The second is the coincidence of $x_p(t_0)$ with the initial state x_0 of the object, *i.e.*

$$x_p(t_0) = x(t_0) \equiv x_0,$$

and, finally, the third—the availability of complete information on the drift of parameters $\xi(t)$.

In practice, strict compliance with these conditions is very difficult, and sometimes simply impossible. A priori information about the parameters ξ (and even more so about their drift) is incomplete and inaccurate. In addition, there are always initial disturbances $e(t_0) = x_0 - x_p(t)$ and uncontrolled permanent disturbances $\pi(t)$. All this leads to the deviation of the real movement under the action of harsh programmed control (6) from the PA $x_p(t)$.

It is necessary to take into consideration the current information about the state of the object in order to improve the quality of control. Due to this, the control law becomes self-regulating, and the PA is stable with respect to the initial and constantly acting disturbances.

The law of PA control with feedback on the object state vector has the form:

$$u(x, x_p, \xi) = u(x, \dot{x}_p, \xi),$$

which, unlike (6), ensures the stability of the PA $x_p(t)$ on a finite time interval $[t_0, t_T]$. A more efficient control law ensures the asymptotic stability of PA and has the form:

$$u(x, x_p, \xi) = U[x, \dot{x}_p + \Gamma(x - x_p), \xi],$$

where Γ is some stable $n\times n$ matrix of gains in the feedback channels. By special selection of the structure and elements of the matrix Γ, it is possible to ensure the specified nature of the decay of transients $l(t) = x(t) - x_p(t)$ [19].

In practice, the parameters ξ of an object can drift in an unpredictable manner in a wide range determined by the restriction (2). External $\pi(t)$ permanent disturbances significantly affecting the accuracy of PA testing are also unknown and cannot be measured by the sensors of the information system of the object. Restrictions on disturbances are given by expression (3).

A specific feature of adaptive control systems is that the lack of information and uncontrolled drift of parameters are compensated by proper processing of sensory information, which are processed by adaptation algorithms that perform self-regulating of control law parameters, as well as by improvement of PA.

The synthesis of the adaptation algorithm with the required properties is closely related to the quality control, which is especially important for the dynamic control of the elements with the SME. Since the adaptation is carried out mainly not only by the parameters of the state $x = x(t)$, but by the quality parameters of the controlled process.

Therefore, we consider the quality function of the form of $\varphi(\tau, t) = \Phi[u(t), x(t), \tau]$, where a magnitude Φ can be measured or calculated at any time t, where τ is some plausible (or real) estimates of unknown parameters ξ, a priori information about which is given by the third expression of system (2). This requirement is necessary for the implementation of adaptation algorithms. The purpose of adaptation is given in the form of inequalities connecting the controls u, the state x and the estimate τ, which can be given by a system of inequalities of the form:

$$\varphi(\tau, t) > 0, \; t \geq t_0. \tag{7}$$

The algorithm for solving these inequalities acts as an adaptation algorithm, the meaning of which is to form acceptable estimates of τ unknown parameters ξ. If inequalities (7) are violated for some $\tau = \tau(t)$, then this indicates the unsatisfactoriness of the current estimate $\tau(t)$ and the need for its correction. If inequalities (7) are satisfied, this indicates the acceptability of both the estimates themselves and the adaptive control law synthesized on their basis.

3. RESULTS

As a result of the study of the thermomechanical and thermoelectric characteristics of titanium nickelide, the possibility of using elements with an SME as thermo-sensitive deformation-force in adaptive-controlled mechanisms and devices has been revealed. At the same time, not only the characteristics of such devices (discrete factors such as temperature, magnitudes of displacements and efforts) has been explored, but also the electrical resistance element itself can be used to define sensor-controlled parameters of adaptation (the specific nature of the change in the electrical resistance of the alloy with the SME at intervals of the forward and reverse martensitic transformations was detected and examined). The nature of changes is also stabilized after the proposed modes of thermal cycling. This greatly simplifies the sensory hardware base of the adaptive control system by combining in one element a sensitive and working body, as well as a control, operating and an informational electrical system.

The simulation of thermo-mechanical and thermo-electric processes of materials and elements with SME, the dynamics of elements and drives based on alloys with shape memory and taking into account the adaptive properties has allowed for the creation of adaptive-controlled drives or actuators, heat regulators and the automation of technological processes.

Analysis of theoretical and experimental studies allows us to outline the following ways to increase the efficiency of TMD:

– The selection of such SMA in which the temperature A_s of the onset of the reverse martensitic transformation differs little from the operating temperature. At the same time, the energy consumption for heating within the dead stroke is reduced to almost zero. According to the results of theoretical calculations, with $T_0 = A_s$ the coefficient of efficiency of TMD may be increased in twice.

– Restriction of deformation of the shape memory. This is due to the fact that at the end of the working stroke the mechanical work produced by the TMD is small, and the proportion of energy consumed for heating increases.

– Conducting preliminary thermomechanical processing of TMD power elements by thermal force cycling. This allows, in addition to stabilizing the characteristics of the drive, to significantly reduce the negative operation of the cycle by reducing the required voltage guidance and initiating a reversible SME.

– Reduction of heat leakage by isolating TMD from the environment. With an increase in the heating rate due to an increase in the power of the supplied energy, the fraction of the dissipated energy also decreases.

– Search for materials that have a lower heat capacity than nickel alloys with titanium, in which more than 2/3 of the energy supplied is spent on heating.

Since the most probable areas of application of elements with the SME are to use them as TMD or actuators, heat regulators, thermal compensators and damping devices, their operating conditions vary considerably in nature and dynamics it is advisable to specify the class of algorithms and typical adaptive control solutions for each area.

– When using elements with SME as TMD, the adaptation algorithms of the continuous class in the terminal control mode are necessary, and the algorithms of the discrete class are applicable only for linear drives.

– Heat regulators based on elements with an SME can be adaptively controlled based on continuous-class control algorithms, which is due to the presence of temperature hysteresis of mechanical characteristics and only regulators (or more precisely, switches) of unidirectional action (*e.g.* emergency) allow the use of discrete algorithms in stabilization mode.

– Adaptive damping devices, due to the high speed of the processes, can be controlled only by continuous algorithms in the homing mode and during this time of guidance should be minimized. In contrast, thermo-compensators due to the low speed of the process do not require adaptive control at all and allow for calculations with sufficient accuracy at the design stage.

4. DISCUSSION

Most adaptation algorithms can be divided into two classes:

– continuous methods, when estimation $\tau(t)$ is defined as solving a differential equation of adaptation;

– discrete algorithms, when the estimate $\tau(t) = \tau(t_k)$ is determined at discrete moments, $k = 0, 1, 2, \ldots$, by recurrent formulas.

The general scheme of continuous algorithms is as follows: the estimate $\tau(t)$ is defined as the solution of a differential equation of adaptation of the form

$$\dot{\tau}(t) = A\left[\tau(t), S(t)\right], \tau(t_0) = \tau_0, t \geq t_0, \tag{8}$$

where $S(t)$ is current information, τ_0—arbitrary initial estimate from Q_ξ set, A—adaptation operator (it is such that the estimates $\tau(t)$ converge to the ideal solution ξ or to some of its surroundings). Discrete adaptation algorithms are described by the following system of relations:

$$\tau(t) = \tau_k,\ t \in [t_k, t_{k+1}],\ t_{k+1} = t'_k + \theta,$$
$$\tau_{k+1} = \tau_k + A[S(t'_k)],\ k = 0, 1, 2\ldots, \tag{9}$$

where τ_k is an arbitrary estimate, t'_k—the first moment of violation of inequalities (7) with $\tau = \tau_k$, $t = t_k$, θ is the time required to calculate the new estimate τ_{k+1} in accordance with algorithm (9) from the information $S(t_k')$ available at the time t_k', A is an adaptation operator.

Thus, the solution of the adaptation problem is reduced to the construction of continuous or discrete adaptation algorithms of the form (8) or (9), generating a trajectory $\tau(t)$, $t \geq t_0$, or a sequence of estimates τ_k, $k = 0, 1, 2, \ldots$, which reduces to some solution of inequalities (7).

The analysis of the technological problem from the standpoint of control theory allows us to distinguish the following typical modes of adaptive control: stabilization of PA, terminal control and homing.

The goal of control in the stabilization mode is to track the PA with a given accuracy ε immediately or after a certain time interval of the transition process $T_p \equiv t_p - t_0$, *i.e.*

$$|x(t) - x_p(t)| \leq \varepsilon \text{ for all } t \geq t_p(t_0, x_0, \xi, \pi).$$

The purpose of the terminal control is to transfer the object from the initial state x_0 to the desired final state x_t in a given time $T \equiv t_t - t_0$, *i.e*.

$$|x(t_t) - x_1| \leq \varepsilon. \tag{10}$$

Finally, the goal of homing has the form (10) with the only difference that the trajectory and time of guidance here is not fixed in advance.

To fulfil the formulated target conditions, it is necessary to synthesize the control law $u = u(t, x, \tau)$ with feedback on the state vector x or the quality function $\varphi(\tau, t)$ and with self-regulation of the parameters τ. Naturally, this law should not depend on unknown parameters $\xi \in Q_\xi$ and disturbances $\pi \in Q_\pi$. When synthesizing and calculating adaptive control laws, their structures and parameters should be chosen in such a way as to guarantee the fulfilment of structural constraints on states and controls over the entire range of motion considered.

4. CONCLUSION

1. A model of the dynamics of adaptively controlled elements and actuators has been developed based on materials with the SME, whose equation solving algorithm acts as adaptation algorithms, on the basis of

which the laws of adaptive control of such elements and actuators can be synthesized.

2. The thermomechanical characteristics of titanium nickelide have been studied and the possibility of using elements with SME as heat-sensitive deformation-force elements in adaptively controlled mechanisms and devices has been substantiated. Ways to increase the efficiency of TMD have been identified.

3. Using of established for TFC relationships gives the possibility to estimate the effect of thermomechanical treatment in a new way and confirm the assumption that obtained experimental results are determined by the methods of research, since single change of the parameters (characterizing effects of memory) are thermomechanical training cycle. The obtained dependences define rational guidance strain values and the required number of thermal cycles N, providing stabilized characteristics of TSE and the optimized parameters formation for memory effects for given TSE geometric characteristics.

4. For elements with SME the use of adaptive control algorithms of continuous class in homing and terminal modes is justified and recommended.

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