Methods of pulsed local action on magnetic mechanical state of ferromagnetic shape memory alloy

N I Gorbatenko¹, V V Grechikhin¹,², I S Kraevskiy¹, A V Kudrya¹ and A L Yufanova¹

¹Platov South-Russia State Polytechnic University (NPI), 132 Prosvesheniya ul., Novocherkassk 346428, Russia
²E-mail: vgrech@mail.ru

Abstract. The task of controlling a positioning system drive with the active element of ferromagnetic shape memory alloy has been considered. The task is to provide the length increment of the active element by a given value from the resultant action – the pulse of magnetic field (or pulse series) with definite amplitude and duration. Methods of solving the task – the methods of tracking and scanning modes of the pulse reversal of the active element – have been suggested. To implement the method of scanning magnetization reversal, it is necessary to introduce a feedback link to reduce the positioning error due to the discrete nature of the effect and have information about the deformation of the element. A specific feature of tracking magnetic reversal is the use of experimental information to exclude overregulation. In testing process, an iterative process has been carried out to correct the mathematical model of deformation, using experimental data. To study the method, a software module has been developed in the LabVIEW graphical programming environment. The data obtained show that application of the method allows to increase the accuracy of controlling positioning systems based on ferromagnetic shape memory alloy.

1. Introduction

A promising direction for the development of positioning systems is the use of ferromagnetic shape memory alloy (FSMA), which has high sensitivity and the ability to change the geometrical dimensions in a wide range under the influence of magnetic, mechanical forces and temperature [1–4]. This allows to increase the accuracy of conversion, expand the range of displacements, and simplify the design of positioning systems. However, there are a number of restrictions on the use of FSMA as active elements. The main ones are the need to make strong magnetic fields, magnetic and mechanical hysteresis, significant effect of temperature change on the FSMA parameters. When making high-speed positioning systems with small weight and size parameters, it is efficient to use local pulsed magnetic fields to control active elements of FSMA. These conditions are met by a positioning system implementing a two-stroke configuration (figure 1). A distributed magnetizing system (1) containing n pairs of coils without ferromagnetic cores which allows to increase speed, reduce weight and size of the device, as well as two active elements (2) made of FSMA, and an actuator (3) is used. The mode of pulsed magnetic reversal of active elements of FSMA with the possibility of controlling the magnitude of magnetic field strength to the elements is used [5]. Also, this approach allows to implement the discrete mode of controlling the deformation of FSMA, improve the accuracy of positioning, increase speed, and reduce weight and overall dimensions of the system.
There is a close interdependence between the factors affecting FSMA, magnetic intensity $H$ and its deformation $\varepsilon$. Problems of mathematical modeling of deformation of local areas of the active element of FSMA of the positioning system have been discussed in the works [6, 7].

The operation principle of the positioning system drive is based on the variation of linear size (deformation) of the active element of FSMA under the influence of magnetic intensity, the vector of which is perpendicular to the plane of resizing. To ensure large deformations of active elements, a pulsed magnetic field with the intensity up to $(350 – 400) \text{ kA/m}$ is created.

We formulate the following control problem. It is necessary to deform the active element by a specified value with a permissible control error $\varepsilon$. The task is to provide the length increment of the active element by a specified value from the resultant impact – a magnetic field pulse (or a series of pulses) with definite amplitude and duration. Further we suppose methods of solving the problem.

2. Methodology

It is possible to implement tracking and scanning modes of pulsed magnetization reversal of the active element of FSMA.

The method of scanning conversion supposed by F.E.Temnikov [8] is that the results of conversion of an unknown input signal are compared with those of the known replacing value, i.e., the difference between a scanning function and a defined one is determined with fixing a zero level of the difference. The scanning function changes with a definite cyclical nature. In the positioning system the magnetic field $H_e(t)$ is taken as a scanning function, and the deformation of the active element $\varepsilon(t)$ is taken as a defined function (figure 2).

The duration of conversion cycle $T_{tr}$ is defined by the duration of magnetization reversal $t_{rem}$ and the duration of pause $t_p$ between the control cycles:

$$T_{tr} = t_p (1 + Q),$$

where $Q$ is a relative pulse duration.

The magnetization reversal duration $t_{rem}$ in a converter of the magnetic field of scanning balancing with steady stepwise changing of the magnetic field is not constant in the range of displacements and depends on the magnitude of magnetic intensity: $t_{rem} = N_e / f_0$, where $N_e$ is a numeric code, $N_e = \text{ent}(H_e / H_k)$, directly proportional to the magnitude of magnetic intensity $H_e$ and, accordingly, to $\varepsilon$. A minimal value of relative pulse duration $Q$ is limited by extremely permissible value of heating of magnetizing winding, depending on the magnetization reversal current $i(t)$. 

![Figure 1. General view of two-stroke positioning system.](image)
We determine the conditions, where the aggregate error $\delta_{H_{sum}}$, equal to the sum of quantization error $\Delta h_k$ and dynamic error $\delta_{H_{dyn}}$ will be minimal. According to [9], the errors $\Delta h_k$ and $\delta_{H_{dyn}}$ will be equal

$$\Delta h_k = \frac{H_e}{N_e}, \quad \delta_{H_{dyn}} = V_{H_e} t_{rem},$$

where $V_{H_e} = dH_e/dt$, is the speed of changing the field $H_e$. In steady stepwise variation law $H_e$, the time of magnetization reversal is equal to

$$t_{rem} = N_e \Delta t_{st}.$$

If $\Delta t_{st} = \text{const}$, then the error $\delta_{H_{sum}}$ can be defined by the formula

$$\delta_{H_{sum}} = \Delta h_k + V_{H_e} N_e \Delta t_{st}. \quad (1)$$

Regarding $N_e$ as a continuous variable, we differentiate the expression (1) by $N_e$ and from the extremum condition we define the optimal value $N_{e0}$, corresponding to the minimum of the aggregate error

$$N_{e0} = \left(\frac{H_e}{V_{H_e} \Delta t_{st}}\right)^{\frac{1}{2}}. \quad (2)$$

With this value $N_{e0}$, error components $\delta_{H_{sum}}$ are equal, correspondingly

$$\delta_{H_{sum}} = \sqrt{H_e V_{H_e} \Delta t_{st}}. \quad (3)$$

Thus, from (2), (3), knowing maximum values of the field $H_e$ and rates of its variation $V_{H_e}$, it is possible to determine the values of quantization step $h_k$ and its time of working-off $\Delta t_{st}$.

In the pulsed magnetization reversal method discussed above, the selection of parameters determining accuracy and speed of positioning is implemented according to equations (1–3) by maximum values of deformation of the active element and, consequently, by magnetic intensity and the rate of its variation. The deformation, values $H_e$ and $V_{H_e}$ can significantly vary. This means that the use of constant $T_{tr}$ and $\Delta t_{st}$ will not promote optimal speed and accuracy of positioning.

To implement the method of scanning pulsed magnetization reversal of the active element of FSMA, it is necessary to introduce a feedback link to reduce the positioning error due to the discrete nature of the effect on the active element of FSMA. It is necessary to get information about the deformation of the element that has occurred. A promising direction of measuring the deformation is the use of sensory properties of the active element [10].

Another approach is the method of pulsed magnetization reversal implementing the tracking mode. As a rule, pulses with constant frequency, duration and, consequently, a constant duty cycle $Q$ are used. The duty cycle $Q$ must correspond to the maximum value of displacement. This means that the duty...
cycle $Q$ has always been overstated, i.e., the converting time is not minimum possible. It is known that
the amplitude of current pulse supplied into the magnetizing winding may exceed the value of constant
current flowing through the same winding into $\sqrt{Q}$.

In control systems, to obtain, in any sense, the optimal control with unknown characteristics of the
controlled process, methods and systems called adaptive are used. If we perform the adaptive regulation
of the duty cycle $Q$ in the process of changing the amplitude of compensatory pulses, then the positioning
time can be significantly reduced (figure 3).

![Figure 3. Pulsed magnetization reversal by tracking balancing method.](image)

It should be considered that in a number of cases when implementing the positioning system, an
additional control condition may be required, – exclusion of overregulation possibility [11]. We regard
this condition in relation to positioning systems with active elements based on FSMA: the actual length
$L_{act}$ of the active element after the control action should be strictly less that the specified value of the
final length $L_{set}$ by the value of allowable control error $\Delta L_c$ (positioning errors) (figure 4).

Displacement control algorithm by the way of deforming the active element based on FSMA includes
the following steps: generation of control pulse for magnetization reversal of the active element;
measurement of actual length $L_{act}$ of the active element; control error calculation $\Delta L_c$; analysis of the
result obtained; determination of parameters of correcting control pulse. Its implementation suggests the
preliminary development of control empiric laws. They present experimentally obtained dependences
of the active element deformation on various control effects in varied initial conditions determined by
the presence of initial deformation of the active element. Various initial deformations of the active
element reproduce the result of action of control pulses at previous iterations of the control algorithm.

![Figure 4. Illustration of additional condition to the active element deformation control.](image)

The specified deformation value of the active element (the specified value of its final length $L_{set}$)
coresponds to the amplitude value of the primary control pulse $U_m^{(1)}$, as well as the table of the amplitude
values of the secondary control pulse $U_m^{(2)}$ as a function of the actual length of the active element
$L_{act}^{(1)}$ after the primary action:

$$ L_{set} = F(U_m^{(1)}, U_m^{(2)}) = f(L_{act}^{(1)}) $$  (4)
Expression (4) presents the analytical record of empiric law of the active element deformation control with one corrective action. In general, several corrective pulsed actions are necessary. In this case the analytical record of empiric control with several corrective actions looks like this:

\[
L_{\text{set}} = F(U_m^{(1)}, U_m^{(2)} = f_1(L_{\text{act}}^{(1)}), U_m^{(3)} = f_2(L_{\text{act}}^{(2)}), \ldots).
\]

Implementation of the method of pulsed action on the active element based on FSMA includes the following stages:

– theoretical determination of the primary control pulse amplitude. Herewith, the necessary control pulse amplitude is determined on the base of mathematical model to achieve the specified final length \(L_{\text{set}}\) of the active element.

– experimental determination of the variation of the results of the primary control action. For this, a series of experiments is carried out, and the variation of values of actual deformation of the active element is determined \(\Delta \varepsilon\) (figure 5).

– adjustment of the primary control pulse amplitude in order to exclude situations of overshoot. Herewith, regarding the value \(\Delta \varepsilon\), the primary control pulse amplitude is corrected (decreased) so that in a series of experiments the maximum active element deformation would not lead to exceeding the given value of the final length of the active element \(L_{\text{set}}\).

– checking the condition of pulse action process completion. It is checked whether the specified control accuracy is ensured as a result of the previous control actions, and, accordingly, whether the required deformation has been performed (figure 6).

\[\text{Figure 5. The variation of values of the actual active element deformation.}\]

\[\text{Figure 6. Condition of deformation process completion of the active element.}\]

At subsequent iterations, the actions of the previous stages are repeated, and not one, but several
series of experiments with the condition of the definite value of the initial deformation of the active element for each series are conducted. These values of the initial deformations are determined by the set of values of the actual final length of the active element detected in an experimental series at the first iteration (after the supply of the primary control pulse). Herewith, the whole set of the mentioned values may be “thinned out” with the accuracy to the permissible control error $\Delta L_{\text{perm}}$.

Consequently, with each successive iteration, the parameters of corrective control pulses are selected, due to the actual increment of the active element at the previous iteration.

3. Results and Discussion
In order to study the supposed method of pulse action on the active element, the computing experiment has been carried out. For its implementation, a software module has been developed in the LabVIEW graphical programming environment.

To enter data into the program, the cluster control element is used. Values of the following parameters are specified: the number of argument values (a control signal amplitude) which will be used to calculate functional dependencies; minimal and maximal amplitudes of the control signal; theoretically minimal and maximal possible increments of the active element length; the exponent parameter in the functional dependence of the active element increment on the control signal amplitude; the specified value of the length increment of the active element; the number of experiments carried out at one definite value of the control signal amplitude determined on the basis of a theoretical model to achieve the given value of the active element length increment; the maximum permissible actual value of the active element length increment.

The program uses the theoretical function of the value of the active element length increment obtained on the basis of mathematical modeling:

$$ dL(I) = dL_{\text{min}} + dL_{\text{max}} \left(1 - e^{-\frac{I-I_{\text{min}}}{p}}\right), $$

where $dL_{\text{min}}$ – minimally possible increment of the active element length after the control action by the pulse with minimum threshold amplitude $I_{\text{min}}$, $dL_{\text{max}}$ – maximally possible increment of the active element length; $I$ – control pulse amplitude; $p$ – exponent parameter.

The graphs of theoretical and actual dependence of the increment size of the active element length on the control signal amplitude have been obtained (figure 7). In Figure: 1 – theoretical dependence of the incremental size of the active element on the control signal amplitude; 2 – actual dependence of the incremental size of the active element length on the control signal amplitude; 3 and 4 – the range of varying the increment of the active element length, depending on the control signal amplitude.

![Figure 7. Theoretical and experimental dependences of the active element deformation value on the control signal amplitude.](image)

Point 5 corresponds to the given value of the active element length increment and, accordingly, the necessary control signal amplitude determined based on theoretical concepts. Point 6 corresponds to
actual value of the active element length increment after the control action by the pulse with the amplitude determined based on theoretical concepts.

The actual dependence of the increment size of the active element length on the control signal amplitude and the range of its variation (figure 8) which is formed due to processing the data of large complex of experiments have been obtained. The graph contains the following elements: 1 – the set of experimentally obtained values of increments of the active element length after control action; 2 – connecting line for displayed experimental values of increments of the active element length; 3 – the specified value of the active element length increment after the control action; 4 – maximally permissible increment of the active element length after the control action.

Figure 8. Experimental values of increments of the active element length after the control action with the given amplitude.

The experimental graph (figure 8) corresponds to the theoretical graph (figure 5). Consequently, the developed software module is an instrument which provides the fulfillment of the first, second and third stages of the method of pulse action on the active element based on FSMA described above. Using the graph element (figure 8), according to the third stage, it is necessary to correct the control signal amplitude so that to avoid the situation of exceeding maximally permissible increment of the active element.

The analysis of the results obtained has shown that the use of the pulsed action method allows to deform the active element of positioning system by the given value with the positioning error not more than 0,5μm.

4. Conclusion
The use of FSMA allows to make high-speed positioning systems with small weight and size parameters. To control active elements of FSMA, it is efficient to use local pulsed magnetic fields. It is possible to implement the scanning and tracking modes of pulsed magnetization reversal of FSMA element. If it is necessary to exclude overregulation to obtain optimal speed and accuracy of positioning, it is advisable to use the method of pulsed magnetization reversal of the active element based on experimental information. The goal of the following works is to study the adaptive method of pulsed action on the element of FSMA, using non-searchable self-tuning systems.

Acknowledgements
The study results are obtained with the support of the project №2.7193.2017/8.9 "Development of scientific bases of design, identification and diagnosis systems for highly accurate positioning with application of the methodology of inverse problems of electrical engineering", carried out within the framework of the base part of State job.
References
[1] Ullakko K at al 1996 Appl. Phys. Lett. 69(13) 1966–1968
[2] Tickle R and James R 1999 Journal of Magnetism and Magnetic Materials 195(3) 627–638
[3] Vasil'ev A N, Buchel'nikov V D, Takagi T, Khovailo V V and Estrin E I 2003 Physics-Uspekhi 46(6) 577–608
[4] Wilson S A at al 2007 Materials Science & Engineering R – Reports 56 1–129
[5] Gorbatenko N I, Grechikhin V V and Shaikhutdinov D V 2015 Metal Science and Heat Treatment 11 609–613
[6] Grechikhin V V, Lozin O I, Kudrya A V, Kudrya N A, Shaikhutdinov D V and Yanvarev S G 2014 Fundamental research 11(4) 744–748
[7] Gorbatenko N, Grechikhin V, Kolomiets A, Kraevskiy I, Kudrya A and Shaykhutdinov D 2017 International Journal of Applied Engineering Research 12(23) 13220–13226
[8] Temnikov F E 1963 Theory of deployment systems (Moscow: Gosenergoizdat Publ)
[9] Ornadskiy P P 1980 Automatic measurements and instruments (Kiev: High school Publ)
[10] Gorbatenko N I, Grechikhin V V, Kraevskiy I S, Kudrya A V and Yufanova J V 2018 IOP Conf. Series: Materials Science and Engineering 441(1) 012020
[11] Grechikhin V V, Kraevskiy I S, Lozin O I, Shaikhutdinov D V and Yanvarev S G 2015 Fundamental research 12 671–675