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SYNTHESIS OF STRUCTURE OF SYSTEM FOR SELF-REGULATION OF ELECTRODE MELTING RATE

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In automation of consumable electrode arc welding it is necessary to have a clear knowledge about the structure of system for a self-regulation of the electrode melting rate. In the given work a general structure of this system is constructed on the basis of analytical description of dynamic processes, proceeding in the welding circuit. A simple structure analysis allows easy obtaining the necessary characteristics of the self-regulation system, including accuracy in a steady mode and time of optimizing the effect of disturbances. Criteria are suggested, that allow selecting those parameters of welding processes from the admissible values, which provide the desirable quick-response of the self-regulation system. Results of comparison of quick-response estimates, obtained by using these criteria, with results of computer modeling, are given. 21 Ref., 5 Figures.

Keywords: *robotic arc welding, consumable electrode, structure of self-regulation system, evaluation of accuracy and quick-response of system*

A wide class of biosystems is known, realizing the self-regulation (homeostas) of processes in live organisms, the structures of which are «synthesized» by the nature itself in the course of a long evolution. A large factual material is accumulated, describing the different symptoms of homeostas [1, 2]. At the same time the problems, referring to the construction of structure itself of such systems, are poorly elucidated in literature. The main problem here consists in the fact that the distinguishing of separate substructures from the general structure, fulfilling the definite functions of the homeostas, and establishment of functional relations between these substructures occurred to be a rather difficult task.

The similar situation is formed in study of one of unique technical control systems, used widely in welding technology, namely the system of arc self-regulation [3–11], more precisely self-regulation of electrode melting rate (EMR). The same as in systems of homeostatic type, there is some uncertainty in EMR concerning its structure and separate elements, fulfilling either functions of the self-regulation. Nevertheless, in robotization of consumable electrode arc welding in shielding gas it is necessary to have a clear idea about the structure of EMR and its parameters.

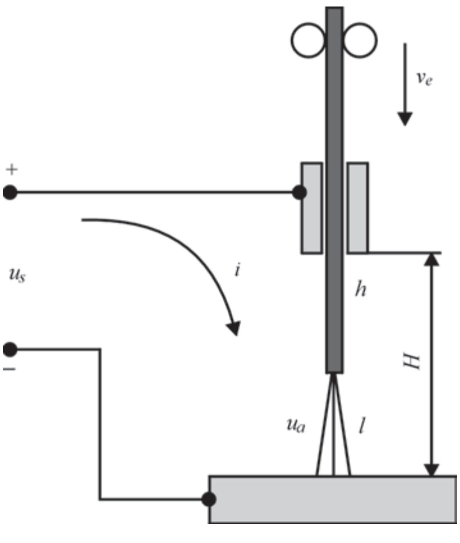

Figure 1. Scheme of welding circuit

It should be noted that problems connected with the construction of EMR structure were described earlier [7, 8], but the structural diagrams, given in the mentioned publications, were rather cumbersome, and, therefore, are hardly suitable for practical application. In the present work the task of synthesis of «curtail» easily visible structure of EMR on the basis of analytic description of well-observed dynamic processes, proceeding in welding circuit of the system, was put.

Construction of schematic diagram of EMR. Figure 1 shows a principal elementary diagram of welding circuit of EMR. At this diagram and in the further description $u_s = u_s(i, t)$ is the voltage, supplied to circuit input from the welding current source; $v_e = v_e(t)$ is the electrode feed speed relatively to current-carrying nozzle edge; $H = H(t)$ is the distance between the nozzle edge and workpiece welded; $h = h(t)$ is the electrode stickout; $l = l(t)$ is the arc length; $u_a = u_a(l, i)$ is the arc voltage; $i = i(t)$ is the welding current.

Let us denote by R: the total electric resistance of supplying wires, a sliding contact in torch nozzle, electrode stickout and workpiece welded, included into welding circuit, and by L: the inductance of welding circuit. The differential equation of the circuit with account for R and L will be written in the form

$$L\frac{di}{dt}+Ri=u_s(i,t)-u_a(l,i). \tag{1}$$

Functions $u_s(i,\ t)$ and $u_a = u_a(l,\ i)$ in the operating range of welding currents will be supposed as continuous and differentiable by their arguments and the arguments themselves as continuous and limited.

The electrode feed speed $v_e(t)$ and rate of its melting $v_m(t)$ are connected with actual value of electrode stickout $h(t)$ by the equation [6]

$$h=h_0+\int_0^t (v_e-v_m)dt, \tag{2}$$

in which h_0 is the initial value of stickout. Dependence of $v_m(t)$ on $i(t)$, according to works [9–11], will be written in the form

$$v_m(t)=Mi, \tag{3}$$

where M is the parameter, characterizing electrical, thermophysical and geometric properties of consumable electrode.

System of equations (1)–(3) will be added with equality

$$h+l=H \tag{4}$$

and differentiated (1), (2), and (4) by time t. Then, by excluding intermediate variables u_a, i, h and l from the formed equations, we shall come to one equation relative to variable v_m:

$$a\frac{d^2v_m}{dt^2}+b\frac{dv_m}{dt}+v_m=v_e+\frac{dg}{dt}. \tag{5}$$

In this equation the following designations are introduced:

$$a=\frac{L}{EM},\quad b=\frac{R_w}{EM},\quad g=\frac{u_s}{E}-H, \tag{6}$$

where $E = \partial u_a/\partial l$ is the intensity of electric field in arc column; R_w is the total resistance of welding circuit:

$$R_w=R+S_a+R_s.$$

Here $S_a = \partial u_a/\partial i$, $R_s = \partial u_s/\partial i$ are the tangents of angles of inclination of static volt-ampere characteristics of arc and welding current source in working point of welding.

Differential equation (5) represents a mathematical model, connecting the electrode melting rate $v_m(t)$ and its derivatives with feed speed $v_e(t)$ and disturbances du_s/dt and dH/dt. This equation will be written in operator form

$$A(p)v_m(t)=v_e(t)+B(p)g(t), \tag{7}$$

where

$$A(p)=ap^2+bp+1;\ B(p)=p\left(p\equiv\frac{d}{dt}\right),$$

and the equation of mismatching will be introduced for consideration

$$\varepsilon(t)=v_e(t)+B(p)g(t)-v_m(t). \tag{8}$$

Let us compare the schematic diagram (Figure 2) with equations (7) and (8). In this diagram the function

$$W(p)=\frac{K}{p(Tp+1)} \tag{9}$$

is a transfer function of opened part of system, and by K and T in expression (9) the following relations are designated

$$K=\frac{1}{b}=\frac{EM}{R_w},\quad T=\frac{a}{b}=\frac{L}{R_w}. \tag{10}$$

Analysis of EMR structure. As is seen from Figure 2, the EMR represents a closed system with a rigid negative feed back by electrode melting rate $v_m(t)$. As input effects the $v_e(t)$ and $g(t)$ are used. Mismatching $\varepsilon(t)$ essentially controls the electrode melting rate $v_m(t)$ through the transfer function $W(p)$.

The standard appearance of schematic diagram of EMR allows using the results of theory of systems of automatic control in its analysis. In particular, only by the presence of multiplier p in denominator of transfer function (9), according to works [12, 13], it is possible to state at once that EMR possesses a type 1 servo system with respect to effects of $v_e(t)$ and $g(t)$. It means that when $v_m(t) = v_{e0}$ = const and $g(t) = g_0$ = const, the set error $\varepsilon_\infty=\lim\limits_{t\to\infty}\varepsilon(t)$ is equal to zero. Consequently, in steady mode in accordance with expression (8), equality $v_m(\infty)$ is fulfilled, which denotes that EMR provides the stabilization of electrode melting rate $v_m(t)$ at the preset level v_{e0}.

If $v_e(t) \neq$ const, and changed by some law, then $v_m(t)$ will be also changed by the same law, i.e. rate $v_m(t)$ will be as if «follow» the rate $v_e(t)$. In this case EMR, according to the terminology of work [14], represents a servo system. In particular, if $v_e = v_{e0} + \Delta v_e \sin \omega t$, where Δv_e is the amplitude, and ω is the angular frequency, then after completion of transfer process the rate $v_m(t)$ will be changed as follows:

$$v_m(t)=v_{e0}+\Delta v_m(\omega)\sin[\omega t+\varphi(\omega)].$$

Here it is necessary to take into consideration that the amplitude $\Delta v_m(\omega)$ and phase shift $\varphi(\omega)$ depend on ω and, as shown in work [15], on $\Delta v_m(\omega) \to 0$ at $\omega \to \infty$.Consequently, the frequency ω, at which it is supposed to perform the oscillating movement $v_e(t)$, it is necessary to select from the condition $\omega < \omega_c$, where ω_c is the boundary frequency of EMR pass band. As

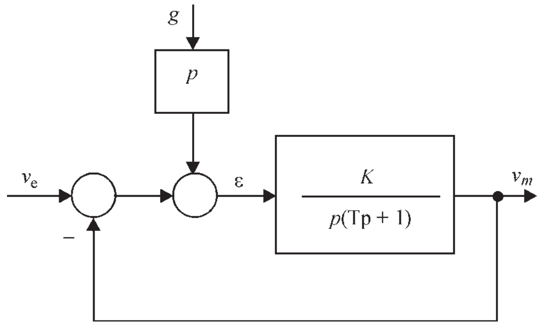

Figure 2. Schematic diagram of EMR

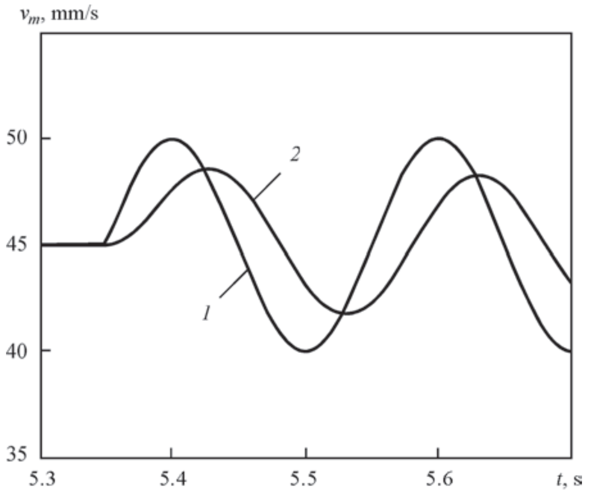

Figure 3. Reaction of electrode melting rate $v_m(t)$ on harmonic effect of $v_e(t) = 45 + 5\sin(31.4t)$

to the case when $g(t) \neq \text{const}$, then at $v_e(t) = v_{e0}$ the rate $v_m(t)$, as is seen from schematic diagram of EMR, will «follow» the change of dg/dt. This is remarkable property, widely used in pulse-arc technologies of welding [16–19].

Let us now address the problem of EMR quick-response. We shall consider the case when the limitation is imposed on value R_w, as, for example, at the underwater arc welding [20]. But there is a feasibility to change in some limits the values of parameters L, E and M. As a measure of quickness of proceeding the transient processes in this case, a generalized estimate of numerical value of coefficients of characteristic equation $T\lambda_2 + \lambda + K = 0$, corresponding to the differential equation, can serve (5):

$$\Omega = \sqrt{\lambda_1\lambda_2} = \sqrt{\frac{K}{T}}. \qquad (11)$$

In this expression λ_1, λ_2 are the roots of equation $T\lambda_2 + \lambda + K = 0$. Estimation Ω in the theory of control is called as mean-square root [12]. Increase in Ω by β times leads, according to work [12], to the decrease in the transient process decay time by β times.

Taking into account the relations (10), the formula (11) will take the form

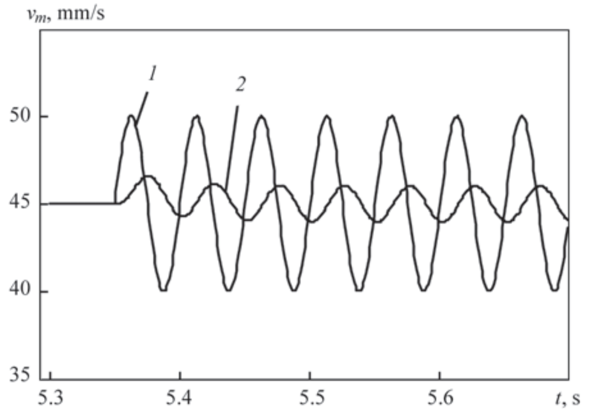

Figure 4. Reaction of electrode melting rate $v_m(t)$ on harmonic effect of $v_e(t) = 45 + 5\sin(125.6t)$

$$\Omega = \sqrt{\frac{EM}{L}}. \qquad (12)$$

From this formula it is seen at once, that to increase the EMR quick-response it is necessary to decrease L and increase E and M. The range of allowable values L, according to works [4, 5], is rather wide (10^{-3}–10^{-4}) H. The values of parameter E depend, as is known, on shielding gas composition, used in arc welding. From the data, given in work [4], in CO_2 welding the parameter E takes a values in the range from 1.7 up to 3.3 V/mm, and in argon welding it is from 0.6 up to 1.3 V/mm. As to parameter M, then its value depends greatly on electrode diameter d. This dependence, according to works [6, 21], has the following form: $M = \psi/d^2$, where ψ is the coefficient, characterizing the thermophysical properties of electrode material (density, temperature of melting (and boiling), specific heat capacity and electron work function). Consequently, with decrease in d the value of parameter M is sharply increased. Thus, there is a principal possibility for providing the acceptable quick-response of EMR.

In Figures 3–5 the results of computer modeling of processes in EMR are given, obtained at the following values of parameters of welding circuit and mode of robotic arc welding: $u_s = 30$ V; $H = 17$ mm; $R_1 = 0.025$ Ohm; $R_s = 0.01$ V/A; $S_a = 0.005$ V/A; $L_1 = 0.0001$ H, $L_2 = 0.001$ H.

The arc welding was modeled in argon ($E_1 = 1.7$ V/mm) and in CO_2 ($E_2 = 3$ V/mm) by electrodes of two different diameters: $d_1 = 1.2$ mm ($M_1 = 0.37$ mm/(s·A)) and $d_2 = 0.8$ mm ($M_2 = 0.82$ mm/(s·A)). As typical effects the functional relations, described by the following analytical expressions, were used:

$$v_e(t) = \begin{cases} 45, & t < t_*, \\ 45 + 5\sin\omega t, & t \geq t_*, \end{cases} \qquad (13)$$

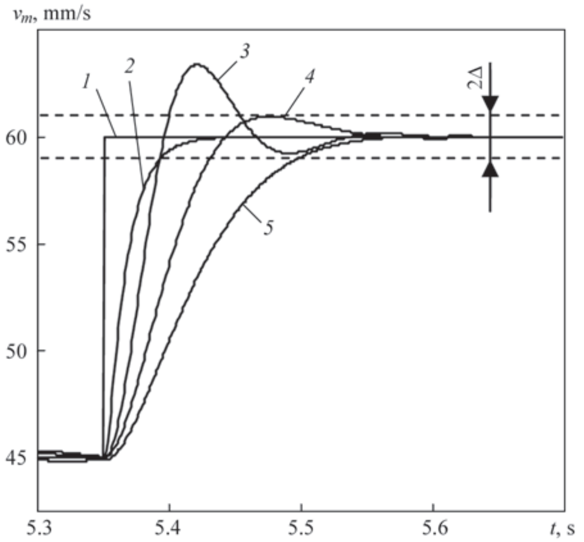

Figure 5. Reaction of electrode melting rate $v_m(t)$ on jump in its feed speed $v_e(t)$ at different combinations of parameters L, E and M

$$v_e(t) = \begin{cases} 45, & t < t_*, \\ 60, & t \ge t_*, \end{cases} \qquad (14)$$

where $t_* = 5.35$ s.

In Figures 3, 4 the digit *1* marks the graphs of functions (13), and digit *2* marks the reaction $v_m(t)$ on effect $v_e(t)$, expressed by this function. Moreover, in Figure 3 the graph $v_e(t)$ is plotted at $\omega = 31.4$ s^{-1}, and in Figure 4 — at $\omega = 125.6$ s^{-1}. It is seen from these Figures that, as was expected, the rate $v_m(t)$ in a steady mode is changed by the same law as the rate $v_e(t)$, and its amplitude is decreased with increase in frequency ω.

In Figure 5 the digit *1* marks the graph of function (14), and digits (2–5) mark the reaction of $v_m(t)$ on effect of $v_e(t)$ at different combinations of parameters L, E and M: curve *2* was obtained at L_1, E_1 and M_2; curve *3* — at L_2, E_2, M_2; curve *4* — at L_2, E_1, M_1; curve *5* — at L_2, M_1, E_1.

It is seen from this Figure that the time of regulation τ_c (time, after the lapse of which, the difference $|v_m(t) - v_{e0}|$ does not exceed some preset value Δ) depends greatly on combination of parameters, given in formula (12). Parameters τ_c and Ω are related, according to work [12], by ratio

$$\tau_c = \frac{4.8}{\Omega}. \qquad (15)$$

Consequently, by calculating the values by formula (12),

$$\Omega_2 = \sqrt{\frac{E_2 M_2}{L_1}} = 156.8\ \text{s}^{-1}, \Omega_3 = \sqrt{\frac{E_2 M_2}{L_2}} = 49.6\ \text{s}^{-1},$$

$$\Omega_4 = \sqrt{\frac{E_2 M_1}{L_2}} = 33.3\ \text{s}^{-1}, \Omega_5 = \sqrt{\frac{E_1 M_1}{L_2}} = 25.1\ \text{s}^{-1}$$

and by substituting them successively into formula (15) we shall obtain

$$\tau_{c2} = 0.031\,\text{s}, \quad \tau_{c3} = 0.097\,\text{s},$$
$$\tau_{c4} = 0.144\,\text{s}, \quad \tau_{c5} = 0.191\,\text{s}. \qquad (16)$$

Comparison of calculated values (16) with the results of modeling, given in Figure 5, shows a good their correlation. Thus, the estimation of quick-response Ω or time of regulation τ_c can be easily obtained, not solving the differential equation (5), but using the simple relations (12) and (15).

Conclusions

1. On the basis of analytic description of well-observed dynamic processes, proceeding in welding circuit, the structure of EMR is constructed, the analysis of which allows quite simple obtaining of necessary idea about the main properties of EMR. In particular, it is seen from the schematic diagram of EMR, that it possesses a type 1 servo system and, depending on law of changing $v_e(t)$, can provide either stabilization of electrode melting rate $v_m(t)$ at the preset level v_{e0}, or «follow» the changes $v_e(t)$ or dg/dt.

2. Criterion Ω, used in this investigation, allows also a simple (without preliminary modeling or special experiments) selection of those parameters from allowable parameters E, M and L, which provide the necessary quick-response of EMR.

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