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Algorithm for numerical simulation of an electromagnetic pulse actuator with respect to the condition of permissible heating

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Algorithm for numerical simulation of an electromagnetic pulse actuator with respect to the condition of permissible heating

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Abstract. The results of numerical simulation of the dynamical characteristics of an electromagnetic pulse actuator with respect to the condition of its permissible heating are presented. The short-time operation mode is considered. This mode is featured by constant power applied to the actuator and the necessity to switch off the actuator when its temperature has achieved the limit value and then to cool the actuator until ambient temperature. The subject of research is the development of the algorithm for numerical simulation of the permissible operation time of the electromagnetic actuator with respect to the permissible heating condition and output energy. The object of the research is the electromagnetic pulse actuator that makes reciprocating motion. The electromagnetic actuator has a moveable part controlled by electromagnetic forces generated by the excitation coil powered by pulse current. The moveable part is reversed by mechanical forces generated by the return spring. The research makes it possible to obtain the relation between the electromagnetic actuator output indicators and its operating period. The algorithm for numerical simulation of the operation process during a short-time mode is presented. The algorithm is verified with the electromagnetic pulse actuator model.

1. Introduction

Electromagnetic actuators of different principles of operation and designation are widely used in various technical fields [1–8].

The practical calculations of electromagnetic actuators are based on static approaches and neglect the dynamics of operation processes [9–11]. The existing calculation methods based on static approaches lead to noticeable calculation errors and they cannot describe exactly dynamic processes.

The investigation of dynamics of processes in electromagnetic pulse actuators is a very actual problem [12–14]. Heating and cooling of the electromagnetic pulse actuators is an urgent problem that requires the development of calculation methods taking into account operation dynamics in different operation modes.

The electromagnetic pulse actuator operates mostly in an intermittent mode described by switching frequency and switched “ON” time duration. When the electromagnetic actuator is switched “ON”, its temperature does not achieve a steady-state value in any operating cycle. When the electromagnetic actuator is switched “OFF”, it cannot cool down until ambient temperature.

2. Materials and Methods

The present paper considers the periodic operation mode of the electromagnetic pulse actuator when applied power is constant during operation time. If the temperature of the actuator elements achieves some average it switches off. Here the applied power is extremely higher than allowable one in long-time mode and can be represented as a sequence of the time intervals "ON" and "OFF".

The equations below have been derived under the assumption that the electromagnetic actuator is a homogeneous body with uniformly distributed heat sources. The electromagnetic actuator thermal conductance is permitted to be ideal.

When initial conditions are zero and operation mode is periodic, with respect to the assumptions in [15], the typical equations of transient temperature oscillations in heating and cooling have the form:

$$\tau(n)_{\min} = \tau(0)\gamma^n + \frac{\tau_s(1-a)\ (1-\gamma^n)b}{1-\gamma}; \tag{1}$$

$$\tau(n)_{\max} = \tau(0)\gamma^n + \frac{\tau_s(1-a)\ (1-\gamma^n)}{1-\gamma}, \tag{2}$$

where $\gamma = \mathrm{e}^{-\frac{t_c}{T_0}}$, $a = \mathrm{e}^{-\frac{t_{on}}{T_0}}$, $b = \mathrm{e}^{-\frac{t_{off}}{T_0}}$, $t_c = t_{on} + t_{off}$ is the operation cycle, t_{on} is the "ON" time, t_{off} is the "OFF" time, n is the number operation cycle, $\tau(n)_{\min}$ is the minimal overheating temperature, $\tau(n)_{\max}$ is the maximal overheating temperature, T_0 is the heating time constant of the electromagnetic actuator, τ_s is the steady-state actuator temperature excess over ambient temperature, $\tau(0)$ is the initial temperature excess over ambient temperature.

If the periodic heating process has the zero initial condition $\tau(0)=0$, n is adequate to the quantity of serial operating cycles until the coil's temperature achieves maximal permissible average value. In this case, long-time operation is limited by allowable overheating when the electromagnetic actuator should be switched off and cooled until ambient temperature.

Dependences of the temperature excess over the ambient temperature on heating and cooling operation mode parameters can be obtained from the equations (1) and (2) at $\tau(0)=0$.

The temperature excess of some average value in the transient mode can be calculated by the formula:

$$\tau(n)_{av} = \frac{\tau(n)_{\max} + \tau(n)_{\min}}{2}. \tag{3}$$

Inserting the equations (1) and (2) to the equation (3) gives the equation for the permissible maximal number of operation cycles:

$$n_{\max} = \frac{T_0}{t_c} \ln\left[\left(1 - \frac{1}{k_o}\frac{2\ (1-\gamma)}{(1-a)\left(1+\dfrac{\gamma}{a}\right)}\right)\right]^{-1}, \tag{4}$$

where $k_o = \dfrac{\tau_s}{\tau_p}$ is the power overload factor, τ_p is the permissible temperature excess.

If $T_0 >> t_c$, then (4) for the maximal number of operating cycles can led to the simpler form:

$$n_{\max} = \frac{T_0}{t_c}\ln\left(1 - \frac{1}{k_o}\cdot\frac{t_c}{t_{on}\left(1-\dfrac{t_{off}}{2T_0}\right)}\right)^{-1}. \tag{5}$$

The power overload factor k_{o} can be expressed as a function of the output energy A_{st} :

$$k_o = \frac{A_{st}\left(1-\eta\right)}{t_{on}\eta\, k_h\left(\vartheta_{ad}-\vartheta_0\right)S_{ref}}\,, \tag{6}$$

where η is the electromagnetic pulse actuator efficiency, k_h is the surface heat-transfer factor, S_{ref} is the electromagnetic pulse actuator cooling area, ϑ_{ad} is the permissible temperature with respect to the heating condition, ϑ_0 is the ambient temperature, t_{on} is the pulse width of the current in the coil during the operation cycle.

Maximal operation time is $t_{\max} = t_c \cdot n_{\max}$ or with respect to (4):

$$t_{\max} = T_0\, \ln\left(1 - \frac{1}{k_o}\,\frac{2\,\left(1-\gamma\right)}{\left(1-a\right)\left(1+\dfrac{\gamma}{a}\right)}\right)^{-1}. \tag{7}$$

The algorithm for finding the output parameters is performed in the following sequence:

1. The permissible overheating temperature of the electromagnetic actuator is determined

$$\tau_{ad} = \vartheta_{ad} - \vartheta_0\,.$$

2. The of the cooling surface area with respect to the dimensions in figure 2 is determined

$$S_{ref} = \pi\, D\, L\,;$$

3. The mass of steel elements of the electromagnetic actuator construction is determined

$$m_{steel} = m_{eld} - m_{coil}\,.$$

4. The thermal time constant of the electromagnetic actuator with respect to heat transfer to the steel elements is determined

$$T_0 = \frac{c_{coil}\, m_{coil} + \beta_{coef}\, c_{steel}\, m_{steel}}{k_h\, S_{ref}}\,,$$

where β_{coef} is the factor of the heat transfer ratio from the coil to the steel elements, $c_{coil} = 390 J/\left(kg\cdot K\right)$ is the coil copper heat capacity, $c_{steel} = 470 J/\left(kg\cdot K\right)$ is the steel heat capacity.

5. The operation cycle width t_c and the current-off pause t_{on} are determined

$$t_c = \frac{60}{n_{st}}\,;\quad t_{off} = t_c - t_{on}\,.$$

6. If $t_c \le T_0$ then the permissible maximal number of operation cycles with respect to heating condition is determined from (5):

$$n_{\max} = \frac{T_0}{t_c}\ln\left(1 - \frac{1}{k_o}\cdot\frac{t_c}{t_{on}\left(1-\dfrac{t_{off}}{2T_0}\right)}\right)^{-1}, \tag{8}$$

where $k_o = \dfrac{A_{st}\left(1-\eta\right)}{t_{on}\eta\, k_h\left(\vartheta_{ad}-\vartheta_0\right)S_{ref}}$.

7. The maximal operating period of the electromagnetic actuator is determined

$$t_{\max} = t_c \cdot \overline{n}_{\max}\,.$$

3. Results and Discussion

The algorithm is verified with the electromagnetic pulse actuator model developed in MATLAB Simulink (Figure 1). The design of the actuator is stated is Figure 2.

The numerical simulation of the electromagnetic pulse actuator gave capability to obtain the regulating performances (Figure 3) including the maximal number of operating cycles and the maximal operating period of electromagnetic actuator as the functions $n_{\max} = f(A_{st})$ and $t_{\max} = f(A_{st})$ with respect to the condition of permissible heating.

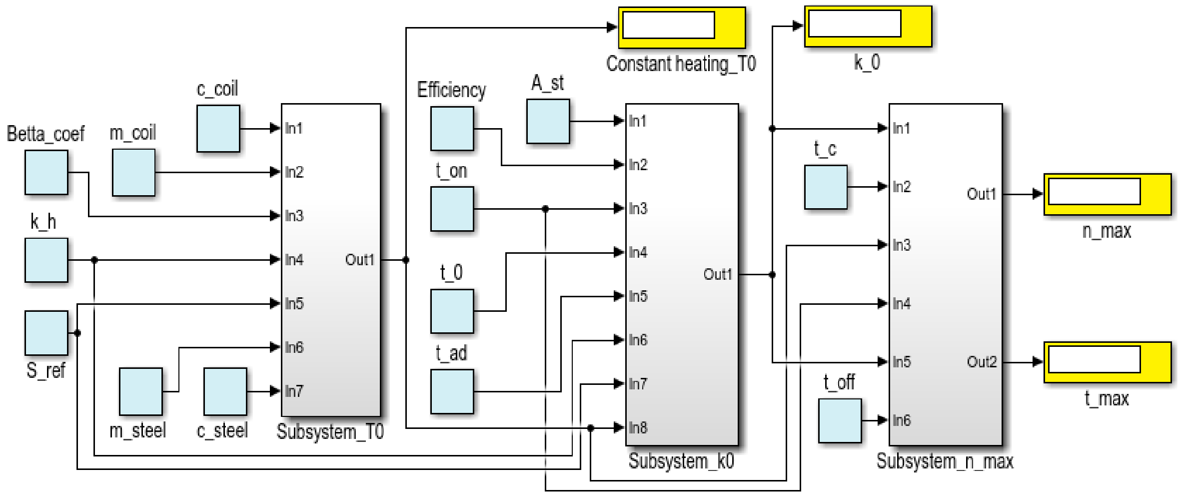

Figure 1. MATLAB Simulink model for numerical simulation

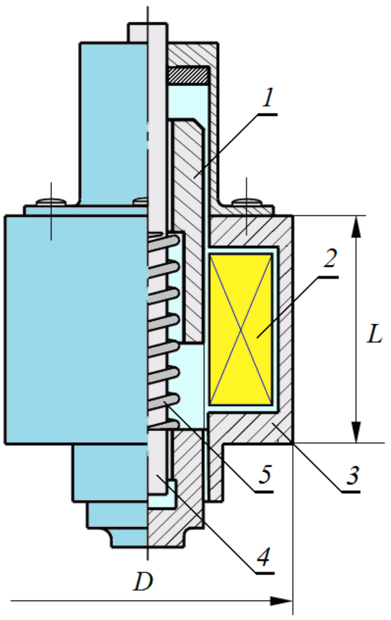

Figure 2. Electromagnetic pulse actuator: *1* – movable part; *2* – coil, *3* – magnetic core, *4* – guide, *5* – return spring

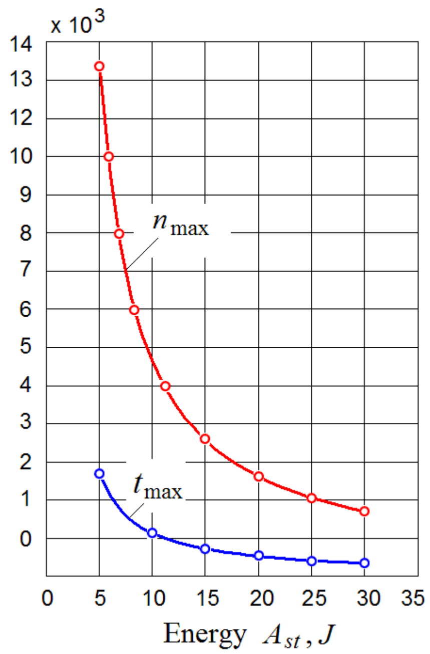

Figure 3. Electromagnetic pulse actuator regulation performance

The parameters of the electromagnetic pulse actuator in figure 2: the movable part frequency is $n_{st} = 300\, st/\min$, the movable part energy control range is $A_{st} = 5...30\ J$, the coil current pulse width is $t_{on} = 0.018\ s$, the electromagnetic actuator efficiency is $\eta = 0{,}35$, the electromagnetic actuator temperature with respect to the heating condition is $\vartheta_{ad} = 100\,^{\circ}C$, the ambient temperature is

$\vartheta_0 = 35\,^{\circ}C$, the heat-transfer factor is $k_h = 10\, W/m^2 \cdot K$, the mass of the copper wire of the coil is $m_{coil} = 2.22\, kg$, the electromagnetic actuator cooling surface diameter and length are respectively $D = 110\ mm$ and $L = 85\ mm$, the electromagnetic actuator mass is $m_{eld} = 6.3\ kg$.

4. Conclusion

The relation between the electromagnetic pulse actuator output indicators and its maximal operating period has been established by the numerical simulation with respect to the permissible heating, dynamics of the operation and output energy. The numerical simulation of the operation process of the electromagnetic pulse actuator with respect to its average temperature has been considered for the calculation of the regulation performance as an example. The obtained expressions describing the operation of the electromagnetic pulse actuator and the algorithm of the numerical simulation can be widely used in practice for the control of the thermal load in the short-term operation mode.

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