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Temperature distribution in multi domain construction of the permanent magnet linear actuator*

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Abstract: The transient thermal model of the permanent magnet linear actuator (PMLA) has been considered. The characteristics of heating have been calculated including the main subdomains of the actuator. The carcasses from various materials have also been considered. The calculations have been verified experimentally and a good conformity was obtained.

Key words: linear actuators, thermal field models, heating curves calculation, finite element model

1. Introduction

The calculation of heating curves is very important in the designing of modern electrical devices [1-3, 7]. The materials used in the linear actuator construction e.g. permanent magnets (PM), insulating materials etc. have different properties and limitations according operation temperature [4, 5, 14]. Thus, it is important to develop appropriate numerical model for determination of the temperature to calculate the nominal current density, which does not causes the overheating of the construction. The properties of NdFeB permanent magnets strongly depend on temperature [1, 5] and we should determine their temperature as accurately as possible.

The finite element model [10] of the PMLA (Figs. 1 and 2a) is presented in the paper. The actuator has been developed in the Department of Industrial Electrical Engineering (Opole University of Technology), and used in the fatigue test stands [9]. The drive of the stand operates continuously. Thus, it is important to determine the nominal parameters, which strongly depend on the thermal properties of the actuator. The determination is very important for the current density, first of all.

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The actuator with the movable carcass on which the winding is wound should be made from a material satisfying demanded requirements. From the mechanical point of view it should be as light and durable as possible. From the electromagnetic point of view it must be nonmagnetic with negligible electric conductance. On the other side it should have high thermal conductivity. Some modern plastics and composites are light and durable. However, they are characterized by low thermal conductivity. The carcass used in our PMLA prototype is made from fiber glass with epoxy resins. The properties of some materials used in the physical model have been included in Table 1. We have also modelled the temperature characteristics for the titan carcass, which is characterized by relatively high thermal conductivity. The model with winding made from glued wires has been additionally considered.

Fig. 1. Picture of the PMLA

a) b)

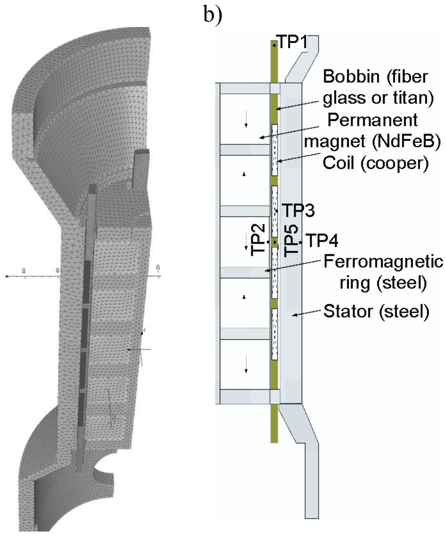

Fig. 2. a) View of the halved PMLA model in the Opera-3D Tempo software, b) cross-section of the calculated model with points where the temperature was calculated and tested

The PMLA has been designed to be implement in fatigue test stands. One of the requirements was low mass of the movable part due to relatively high frequency of the oscillating operation. To obtain high magnetic force/mass ratio, a construction with movable winding has been designed and build (Fig. 2b). The heating curves have been obtained at different points (Fig. 2b). The temperature field has been analysed as well.

2. Mathematical model

The heating of the mass depends on several factors, which concern the material type. They are: thermal conductivity κ [W/(m·K)], thermal capacitance c [J/(kg·K)], mass density ρ [kg/m^3] and generated thermal power density Q [W/m^3]. In the case of transient thermal analysis the parabolic-elliptic partial differential equation for the temperature T has to be solved [6, 8, 11, 13]:

$$\rho\, c \frac{\partial T}{\partial t} - \nabla \bullet (\kappa \nabla T) = Q. \tag{1}$$

For the investigated temperature range the thermal conductivity κ changes slightly. Thus, it has been assumed to be constant and independent from the temperature value.

Including of the boundary conditions in the field model is very important. We assumed two kinds of the boundary conditions. The first one is Dirichlet's condition, which describes the temperature on the outer boundary of the analysed region. The second one concerns the convection phenomenon on outer surfaces of the actuator. It is described by the Equation [6, 12]:

$$\kappa \nabla T \bullet \vec{n} + h(T - T_0) = 0, \tag{2}$$

where $\vec{n}$ is the vector normal to the surface, h is the convection coefficient (in our case $h = 4$ W/(m^{2}K)) and T_0 is the ambient temperature. We know, that the coefficient h for the metal surface changes from 4 to 35 W/(m^{2}K) [5, 6]. However, the range above concerns a plane surface. For our analyzed geometry, the air convection is handicapped. The upper and the bottom bases of the actuator decrease the convection flow.

The material properties used in the model have been included in Table 1.

The heat is generated by the current flowing inside the winding wires (as a Joule heat). The eddy currents could be neglected due to high conductivity of the carcass materials. Thus, the amount of the generated thermal power density in the actuator is described by the equation:

$$Q = \frac{RI^2}{V_{coil}}, \tag{3}$$

where R – winding resistance [Ω], I – current intensity [A], V_{coil} – volume of the winding. In the presented case the current value was $I = 1.2$ A. Thus, the current density value $J = 6$ A/mm^2, and the thermal power density Q = 402299 W/m^3. We have learnt, that the power density depends on the winding temperature. However for our temperature range, the density is not changing strongly. In the calculations of the heating curves (Figs. 3-5), the constant value of the thermal power density has been assumed. In the case of constant excitation current value (PWM supplier), the generated thermal power density increases with the winding temperature.

It is due to the increasing of the winding resistance. Thus, the measured heating curves have to be slightly different from the calculated ones.

Table 1. Thermal properties of the materials used in the physical model [5, 14]

Parameter	Air	Cooper	NdFeB	Steel	Fiber glass	Titan
κ [W/(m·K)]	0.031	401	7.7	54	0.3	7.2
c [J/(kg·K)]	1007	377	502	449	370	560
ρ [kg/m^3]	1.205	8940	7500	7860	8300	4420

3. Calculation results and measurement verification

In the model we have assumed the heating transmission on the way natural convection. The calculations have been carried out for different carcass materials and for different parts of the actuator. In Figure 3 the results obtained for winding made from glued wires has been presented. The properties of the glue have been assumed to be equal to the air properties.

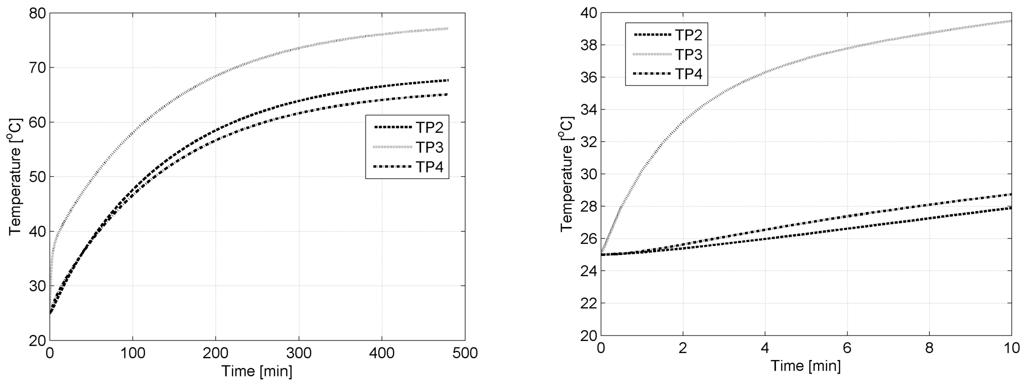

Fig. 3. Heating curves for an actuator without winding carcass

The highest temperature is achieved in the coil (TP3 point), obviously. The permanent magnet (TP2 point) and the outer stator (TP4 point) temperatures are 10 and 13 degree lower, respectively. The shape of the heating curve for winding is different compared to those for stator and PM (Fig. 3b). It is due to the different thermal capacitance of the domains and to the fact, that the winding is the heat source in the model.

In the case of carcass made from fiber glass with epoxy resins, the winding temperature in the balance state is 4 degree lower compared to the glued windings (Fig. 4). The difference between winding and PM temperature are lower (5 degree). It is due to the carcass presence, which transfers the heat from the winding to the PM. The heating curves have similar shape as in the previous case (Figs. 3, 4). Additionally, the temperature of the carcass ends is presented (Fig. 4, TP1 point). It rises relatively slow compared to the other actuator domains (Fig. 4b).

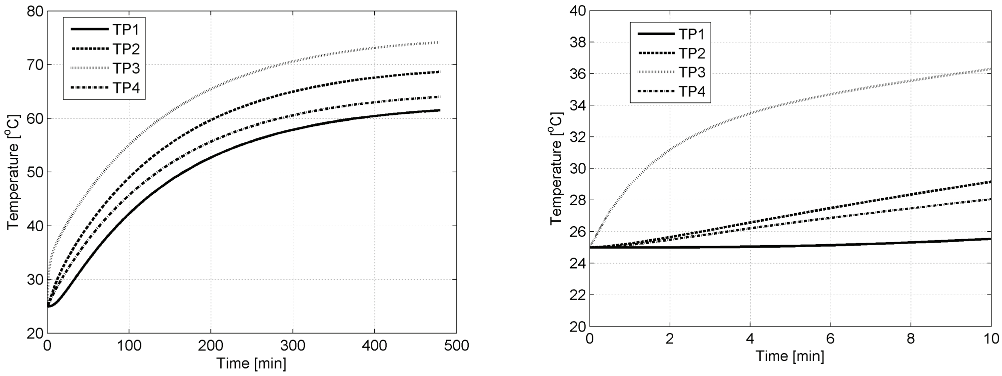

Fig. 4. Heating curves for an actuator with a carcass made from fiber glass with epoxy resins

For the titanium carcass the winding temperature decreases 5 degree compared to the glued wires coil and only 1 degree compared to the carcass made from fiber glass (Fig. 5). The carcass material does not influence the PM temperature (Figs. 4, 5). The titanium carcass ends heat much more intensively compared to the fiber glass carcass (Figs. 4b, 5b, TP1 point). Its temperature is higher, than the outer stator temperature. Taking into account the electric resistivity, the implementation of fiber glass composite is more suitable compared with the titanium one.

Generally, winding and inner part of the carcass are heating faster than the other construction parts. In Figure 6 the temperature field in a cross section of the actuator (a balance state) is presented. Without a forced convection, the temperature distribution is quite homogenous.

Taking into account the electrical and mechanical strength of the winding it is possible to force the current density. In the thermal balance state the temperature difference between the actuator parts does not exceed 12°C. Thus, the permanent magnets and carcass material could be selected under similar temperature.

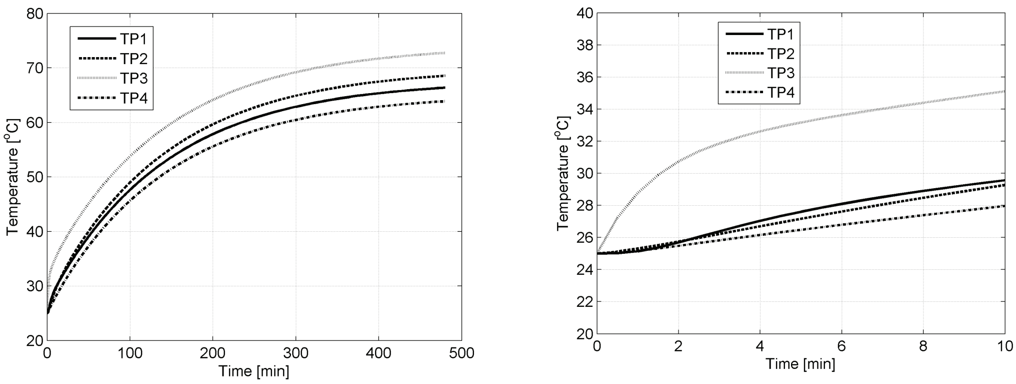

Fig. 5. Heating curves for the actuator with carcass made from titanium

As we mentioned in Chapter 2, the assumption that the power density is constant is a kind of simplification. In a transient model it is difficult to take into account this phenomenon. Thus, the calculations using a static thermal model have been carried out, additionally. In the static model only the balance temperature could be obtained. In Figure 7 the calculation results vs. current value have been presented. In the first case a model with constant power thermal density has been calculated (Fig. 7a) and in the second case a model with variable winding resistance and constant current density, and thus with variable power thermal density has been analyzed (Fig. 7b). A dedicated iterative algorithm has been developed to obtain the proper value of the temperature. As it is visible in Figures 7a and 7b the differences between models are quite significant (35-40 degree). It means, that the phenomenon of resistance variation due to temperature changes has to be taken into account in the thermal calculations of actuators and motors. This phenomenon will be implemented in future mathematical transient models of the actuator.

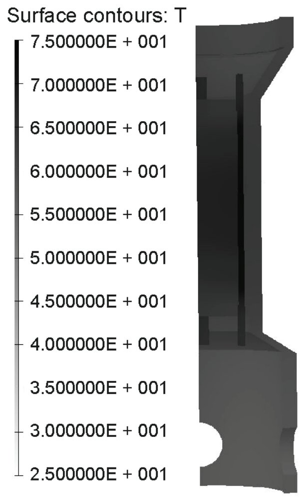

Fig. 6. Thermal field in an actuator with a carcass made from fiber glass with epoxy resins

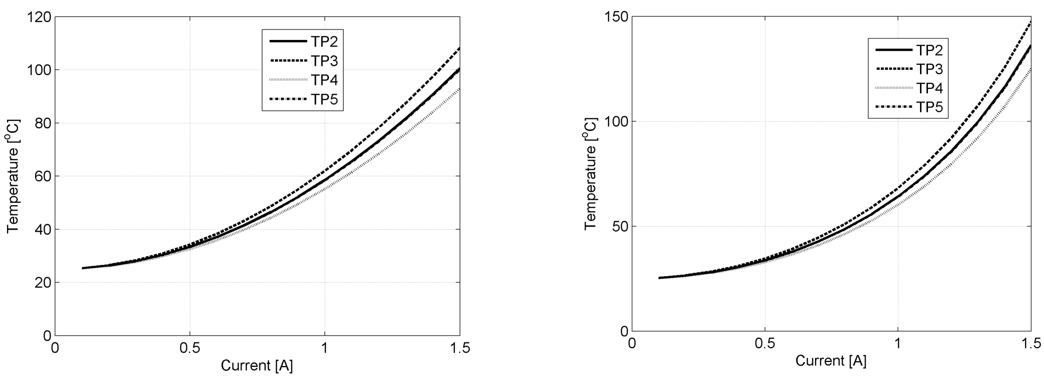

Fig. 7. Static temperature of the chosen actuator points vs. current density value:
a) constant power, b) constant current value

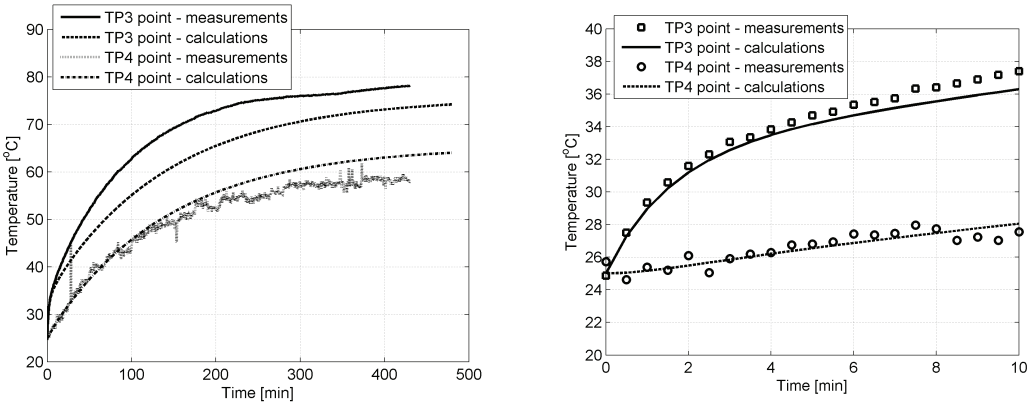

Fig. 8. Measurement verification (T_0 = 25°C, I = 1.2 A):
a) whole heating curve, b) zoomed initial part of the heating curve

The measurement verification has been carried out for the actuator with a fiber glass carcass. The current was I = 1.2 A (J = 6 A/mm^2). The temperature of the winding and outer stator surface has been measured using the infrared camera. There is a quite good agreement between calculated and measured heating curves (Fig. 8). The differences for the winding temperature are due to the constant thermal power density assumption in the mathematical model. The differences in the case of outer stator surface temperature are due to the measurement error (it was difficult to determine the proper thermal emisivity) and due to the problems with determination of convection coefficient h. The coefficient h value has been obtained from tables and from initial thermal calculations.

4. Conclusions

Because of very thin carcass tube (1 mm) the type of the carcass material does not influences the temperature distribution in the actuator considerably. Thus, in the presented construction, it is important to take into account the electrical and mechanical parameters of the movable part. However, in the construction where high forces are needed, the cross section of the winding has to be relatively big, and the thickness of its carcass should be thick. The case will be investigated in the future.

In the calculation model it is important to take into account the variations of the winding resistance due to the temperature changes. The error rising from neglecting this phenomenon is about 10% in our case (410 K compared to the 370 K). However it is difficult to take into account this phenomenon in the transient model, it should be used at least in the static one.

It is not cost-effective to solve the diffusion equation for the time up to balance of temperature in the construction. The calculation time, in that case is 4 times longer than the real heating of the object (using an four core Intel Xeon 3.2 GHz processor with 32 GB RAM). Thus, in such cases where the information about heating curve is not important, it is better to use a static thermal model.

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