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THE THERMAL ANALYSIS OF A STEPPER MOTOR USED IN SPACE APPLICATIONS

ANALIZA TERMICĂ A UNUI MOTOR PAS CU PAS UTILIZAT ÎN APLICAȚII SPECIALE

Ioana IONICĂ[1], Alexandru MOREGA[2], Cristian BOBOC[3]

Abstract: *In this paper we aim to analyze the heat transfer of a stepper motor in frameless configuration under space conditions. Several models with different boundary conditions and different values of emissivity were calculated. A thermal model for challenging environmental conditions, with thermal insulation boundary conditions on stator is presented. Inside the motor subassemblies, the heat transfer will be made through conduction and between the motor and the environment by radiation. Using numerical analysis, it will be possible to determine the moment when the winding temperature reaches the maximum value allowed for the stepper motor in accord with the Technical Specification, in space conditions.*

Keywords: stepper motor, thermal analysis, FEM, space conditions, numerical analysis.

Rezumat: *În această lucrare ne propunem să analizăm transferul de căldură al unui motor pas cu pas în configurație frameless în condiții de spațiu. Au fost calculate modele diferite din punct de vedere al condițiilor la limită și al valorilor emisivității. Este prezentat un model termic pentru cele mai dure condiții de mediu, considerându-se izolare termică pe stator. În interiorul motorului, transferul de căldură se va face prin conducție și între motor și mediu prin radiație. Cu ajutorul analizei numerice se va putea determina momentul în care temperatura din înfășurare atinge valoarea maximă admisă pentru motorul pas cu pas conform Specificației Tehnice, în condiții de spațiu.*

Cuvinte cheie: Motor pas cu pas, analiză termică, FEM, condiții de spațiu, analiză numerică.

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1. Introduction

A stepper motor (SM) transforms digital pulses into mechanical rotation. Under the discrete control signals applied to the windings, these SMs make incremental angular movements with a certain torque [1]. The SMs are widely used in applications requiring a specific positioning and repeatability – spacecraft instrumentation system [2], to control drum actuators [3] or to be used in actuators to deploy and point various equipment. To study the SMs, intensive theoretical and experimental work was done [4]. This paper studies a hybrid SM with a specific construction that foresees the advantages of the two other SMs types, variable reluctance and permanent magnet.

For space applications, the hybrid SMs must work in harsh environments. The requirements of the motor given by the application stated in the Technical Specification in which it is used, including the environmental conditions in which the engine operates, will determine the input data of the heat transfer problem.

The two categories of equally essential requirements are the general ones for operating (electrical, mechanical, and thermal) and the environmental ones (vacuum and radiation stability, resistance to AO – atomic oxygen). Other aspects have also to be considered, such as the effects of the environment (if is operating on LEO – Low Earth Orbit or GEO – Geostationary Orbit), the constraints applicable to the materials (temperature, vacuum, thermal cycles, chemical - corrosion, galvanic compatibility, atomic oxygen, moisture absorption/desorption, fluid compatibility), if the materials will degrade over time, the system in which the motor will be integrated, the interfaces [5].

The heat transfer analysis addressed in this paper establishes the thermal behavior of the SM under space conditions. The SM is studied in [6–9], where the detent torque (the torque with the windings not energized) is of concern. In some SM applications, position holding must occur without energy consumption [10–13].

2. The heat transfer mathematical model

In this paper, three-dimensional numerical models are used to evaluate the thermal behavior of the SM using software that implements the finite element method [5, 14]. Therefore, it will be possible to determine when the winding temperature reaches the maximum allowable value as stated in the Technical Specification for the SM under space conditions.

This paper presents the analysis, development, and presentation of three-dimensional numerical models for a hybrid SM. The motor is designed for applications involving actuators for deploying and pointing various equipment. To study heat transfer in the SM, three-dimensional numerical models are used using the finite element method [14, 15].

The heat transfer problem is solved for thermal conduction and thermal radiation. Mathematical models are developed and analyzed for estimating the temperatures in the SM winding in transient regimes, with an internal heat source represented by the motor winding. The 3D models reflect its constructive solution, but certain simplifying assumptions are considered (no sheets are used for the stator stack, but solid material, and no conductors are considered but solid material for the winding).

Electromagnetic waves carry out the heat transfer by thermal radiation. Thermal radiation is emitted by any substance with a finite temperature and is essentially a process related to the surfaces of bodies [15]. The Stefan-Boltzmann law gives the maximum heat flux at which the surface of a body may emit thermal radiation, called an ideal radiator or blackbody [15]. The emissivity values in the literature are only approximate values for actual materials. An emissivity is a number between 0 and 1, equal to 1 for the ideal radiator or black body. The radiative heat flux emitted by an actual "gray" surface is a fraction of that emitted by the black surface [15].

The equation for the heat transfer that occurs by conduction between solid parts in the transient regime is

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q\ , \tag{1}$$

where ρ [kg/m^3] is the density of the material, C_p [J/kg K] is the heat capacity, t [s] is the time, T [K] is the temperature, k [Wm^{-1}K^{-1}] is the thermal conductivity and Q [W/m^3] is the heat source.

Between the stator and the environment, radiation was considered

$$-\mathbf{n} \cdot (-k\nabla T) = h\big(T_{inf} - T\big) + E(G - \sigma T^4), \tag{2}$$

$$(1 - E)G = J_0 - \mathrm{E}\sigma T^4, \tag{3}$$

where T_{inf} [K] is the reference temperature, E is the surface emissivity, T [K] is the ambient temperature, J_0 [W/m^2] is the surface radiosity, G [W/m^2] is the ambient irradiance and σ is the Stefan – Boltzamann constant ($\sigma = 5.67\times10^{-8}$W/m^{2}K^4). Although in relation (2) a convection component for heat transfer at the boundary is also presented, in the numerical model only radiation at the boundary of the motor with the environment will be considered.

3. Thermal studies for a stepper motor

In the numerical study of this SM, three-dimensional numerical models for transient thermal analysis of the presented motor were used to observe the temperature distribution in the motor.

The SM (Fig. 1) has a stator stack (1), stator winding (2) and a rotor which has 2 half-armatures (3) with a magnet (4) between them. It has 80 teeth on the stator and 90 teeth on the rotor. The motor is constructed using hard magnetic materials (rare earth permanent magnets), Iron Cobalt alloy for the stator stack and copper for the winding. The rare earth magnets are of Sm2Co17 28H type and are characterized by remanent inductances of 1.09 T.

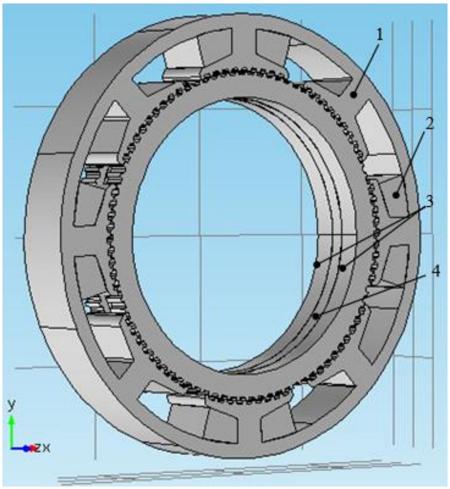


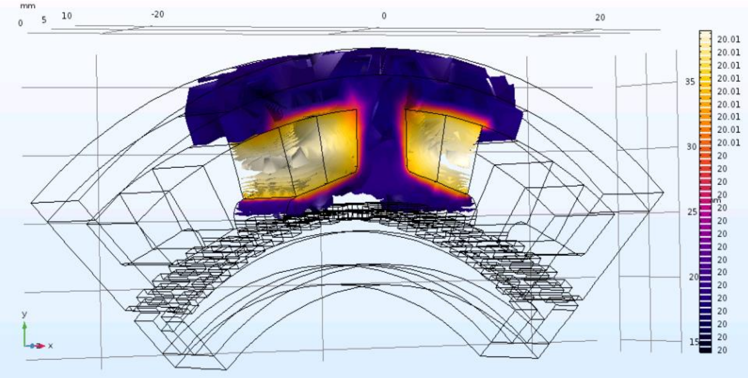
Figure 1. The constructive parts of the stepper motor

In the thermal field study, as a working hypothesis, several variants in which the boundary conditions will consider different values of the emissivity of the motor surfaces varying in the range of 0.2÷0.8 will be numerically analyzed. The current considered is 0.28 A.

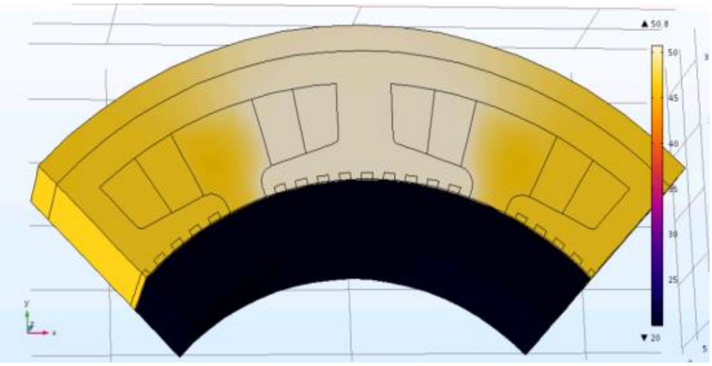
The simplified thermal model was realized for two variants. The first variant considers the motor not fully embedded (only for stator stack length), and the second variant considers the engine fully embedded (with a case higher than the length of the winded stator). Several constructive solutions, including shaft and case, were also considered in numerical modeling.

The thermal model considers the worst environmental conditions, with thermal insulation boundary conditions on stator and rotor parts.

The postprocessing results for the numerical thermal model having the stator completely insulated are presented below:



a) $t = 0$ min. $T = 20$ °C.



b) $t = 5$ min. $T = 50.8$ °C.

Figure 2. The model results of the numerical analysis.

Below is presented a table summarizing the results of the simplified thermal model:

Table 1. **Summary of thermal model results**

Stepper geometric characteristics		**Boundary conditions**		**Time [min]**	**Maximum temperature – T_{max} [°C]**	**Time [min]**	**Maximum temperature – T_{max} [°C]**
The motor not fully embedded	With shaft	Stator complete insulated		10	77.3	30	191
		Surface to surface radiation	ε=0.2	10	77.24	30	190.43
			ε=0.5	10	77.24	30	190.43
			ε=0.8	10	77.24	30	190.43
		Totally radiant	ε=0.2	20	112	113	204
			ε=0.5	20	111	100	198
			ε=0.8	20	110	100	192
	Without shaft	Stator complete insulated		10	77.3	30	191
		Surface to surface radiation	ε=0.2	10	77.25	30	190.44
			ε=0.5	10	77.25	30	190.44
			ε=0.8	10	77.25	30	190.44
		Totally radiant	ε=0.2	15	93	102	204
			ε=0.5	15	92.1	102	198
			ε=0.8	15	91.4	182	191
The motor fully embedded	With shaft	Stator complete insulated		20	98.1	45	193
		Surface to surface radiation	ε=0.2	20	98.03	45	192.23
			ε=0.5	20	98.03	45	192.23
			ε=0.8	20	98.03	45	192.23
		Totally radiant	ε=0.2	20	88.3	200	220
			ε=0.5	20	86.4	190	173
			ε=0.8	20	82.6	187	150
	Without shaft	Stator complete insulated		20	98.1	45	195
		Surface to surface radiation	ε=0.2	20	98.04	45	192.24
			ε=0.5	20	98.04	45	192.24
			ε=0.8	20	98.04	45	192.24
		Totally radiant	ε=0.2	20	88	200	220
			ε=0.5	20	86	82	175
			ε=0.8	20	82.3	172	150

The variant in which the thermal model for the motor not fully embedded – without shaft is presented below. For the stepper without shaft, the geometry model is presented in Fig. 3.

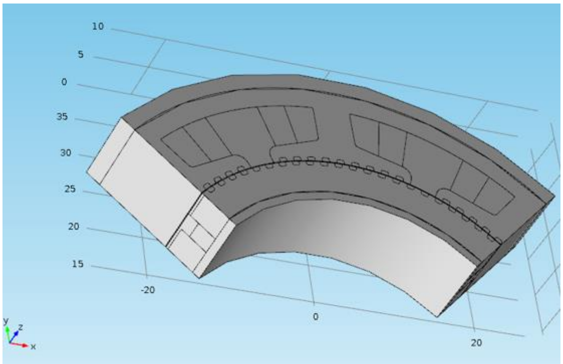


Figure 3. The constructive elements of the SM not fully embedded without shaft

In simulations, a quarter of the motor was considered. Therefore, for boundary conditions, symmetry was used.

Several models with different boundary conditions and different values of epoxy resin emissivity were calculated.

- **Stator complete insulated**

For this case, the stator was considered complete insulated. The results obtained are presented in Fig. 4.

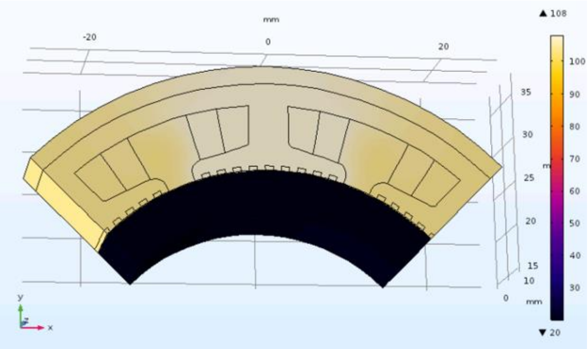


Figure 4. Temperature distribution at t=15min

- **Surface to surface radiation**

At this version, surface to surface radiation boundary condition was used at the airgap boundaries. Three models, different from the epoxy resin surface emissivity point of view were calculated. Below is presented the temperature distribution in the SM with the variant in which the epoxy resin surface emissivity is 0.2. The temperature values for all emissivity values at different time are presented in Table 1. The maximum temperature value at t=30 min reaches 190 ºC for the three variants which considers the epoxy resin surface emissivity of 0.2, 0.5 and 0.8.

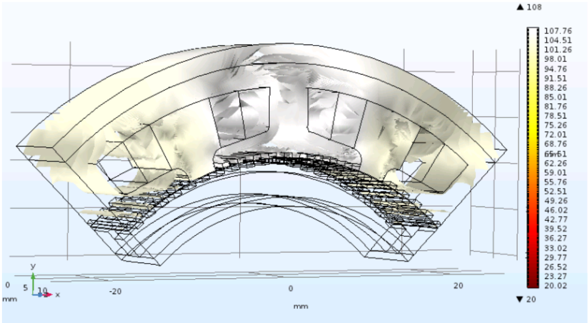


Figure 5. Temperature distribution at t=15min

It can be observed that surface to surface radiation boundary condition is not sufficient for temperature to stabilize at t=30min and the change of surface emissivity coefficient has very small influence on the results.

- **Totally radiant**

At this version, boundary conditions of totally radiation were used. Three models, different from the epoxy resin surface emissivity point of view were calculated. Below is presented the temperature distribution in the SM with the variant in which the epoxy resin surface emissivity is 0.2.

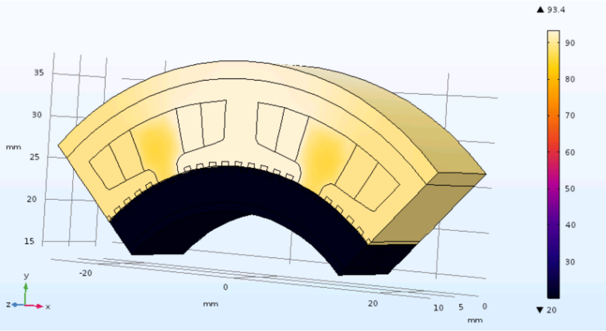


Figure 6. Temperature distribution at t=15min

In this case, compared with the previous situation when only surface to surface radiation was used, the temperature stabilizes at t = 160 min.

Comparing, at *t* = 15 min, the version of epoxy resin with surface emissivity 0.2 and 0.5, respectively, we obtained 106 ºC and 93 ºC. This, a better behavior, can be observed in the second case.

4. Conclusions

This paper presents the thermal analysis of a stepper motor using the three-dimensional numerical model under special space conditions. Thus, heat transfer was achieved only by conduction (within the subassemblies) and radiation (between the subassemblies and the ambient environment).

With the help of thermal modeling, the time in which the temperature in the winding reaches the maximum value allowed for the considered motor was determined.

In the thermal field study, the current value is 0.28 A.

As a working hypothesis, several numerical variants were analyzed considering different values of the emissivity of the SM surfaces varying in the range of 0.2÷0.8. Also, several variants considering the motor fully embedded and with/without shaft are approached and analyzed.

The maximum temperature is in the motor winding (heat source) in all the variants presented.

It can be observed that surface to surface radiation boundary condition is insufficient for the temperature to stabilize at *t* = 30 min, and the change of surface emissivity coefficient has minimal influence on the results. If radiation at the exterior of the motor is accounted for, for the variant in which the epoxy resin surface emissivity is 0.2, the temperature stabilizes, at *t* = 160 min.

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