

Magneto-Thermal Coupled Design of an MRI-Compatible Spherical Actuator

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This paper presents the design and optimization of an iron-less spherical actuator capable of operating in an MRI (magnetic resonance imaging) environment. A coupled electromagnetic-thermal approach is adopted for the actuator design. To reduce optimization time, a 2D axisymmetric electromagnetic model is developed to predict the magnetic field generated by the actuator, while a 1D lumped parameter thermal model (LPTM) is employed to estimate the actuator's heating. These models are validated using finite element analyses. MRI compatibility is ensured through the definition of both electromagnetic and thermal criteria.

Index Terms— Iron-free actuator, Spherical topology, MRI compatibility, Analytical model, Finite elements, LPTM

I. INTRODUCTION

Magnetic Resonance Imaging (MRI) is a non-invasive medical imaging technique that provides high-quality images. It is particularly useful for surgical procedures with real-time image feedback. The benefits of this technique are widely recognized by researchers for robot-assisted surgical interventions [1]. MRI-compatible robotic systems have been developed using ultrasonic and pneumatic actuators [2], which have some drawbacks, such as reduced image quality and poor flexibility while operating.

This work aims to develop a new, more compact, and flexible electromagnetic actuation technology for robot-assisted surgical interventions guided by MRI. A cylindrical actuator rotating around one axis has been studied in [3], it presents very good performances but it has only one Degrees Of Freedom (DOF). We propose in this paper a spherical actuator which can rotate in several directions allowing multiple DOF positioning capabilities.

II. ACTUATOR TOPOLOGY AND MODELING

A simple 2-phase spherical actuator (Figure 1) is proposed. It consists of two perpendicular spherical coils powered simultaneously by 2-phase sinusoidal currents. This generates a rotating magnetic field whose interaction with the static magnetic field B_0 inside the MRI scanner bore leads to electromagnetic torque production.

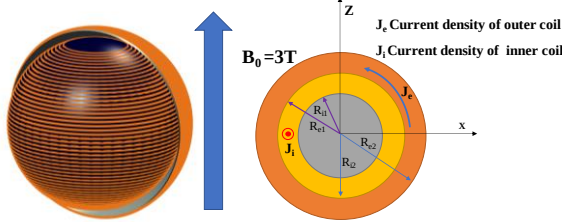


Fig. 1. 2-phase spherical actuator placed in MRI scanner B_0 magnetic field.

A. Electromagnetic model

The torque produced by the actuator is computed using the Lorentz force that B_0 applies on the current density of the coils. In the geometrical configuration presented in Figure 1, the integration over the external sphere's volume, leads to the following formula of the torque along the x-axis:

$$T = \pi^2 B_0 J_e (R_{e2}^4 - R_{i2}^4)/8 \quad (1)$$

This torque remains constant at any position around the x-axis by imposing a current density in the inner sphere such as:

$$J_i = J_e (R_{e2}^4 - R_{i2}^4)/(R_{e1}^4 - R_{i1}^4) \quad (2)$$

To avoid disturbing the B_0 homogeneity leading to artifacts on the image, the maximum field generated by the actuator at a distance R_0 from the rotation axis, does not exceed 1 ppm of B_0 [6]. We have developed a 2D analytical electromagnetic model to calculate the field generated by the actuator's coils. Assuming that each coil has an axial symmetry, in the regions inside and outside the sphere's surface, the magnetic field $\vec{H}$ is both irrotational and solenoidal so it has only 2 components $H_r(r, \theta)$ and $H_\theta(r, \theta)$ in spherical coordinates (r, θ, φ) .

A magnetic scalar potential formulation is adopted to compute the magnetic field distribution [5]. In so doing, the spherical coil of N turns each of which carries a current i is replaced by an equivalent surface current sheet $\vec{K}$ placed on its mean radius R :

$$\vec{K} = \frac{Ni}{2R} \sin\theta \vec{u}_\varphi \quad (3)$$

The PDE arising from using the magnetic scalar potential formulation is solved by separation of variables. The magnetic field components outside the spherical coil is then given by:

$$\vec{H} = \frac{NiR^2}{6r^2} (2 \cos(\theta) \vec{u}_r + \sin(\theta) \vec{u}_\theta) \quad r > R \quad (4)$$

B. Thermal model

A lumped parameter thermal model (LPTM) is developed to evaluate the actuator heating. Assuming that the heat flows in the radial direction only, a 1D model is used. Each spherical layer is represented by 3 thermal resistances (Figure 2) computed in a similar way as in [6]. The node of mean temperature is connected to a heat source corresponding to the Joule losses generated in the coil.

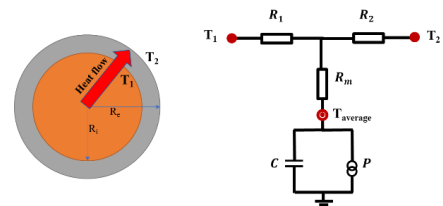


Fig. 2. Elementary block and its equivalent 1D thermal circuit.

The values of the thermal resistances and heat sources are calculated based on the dimensions and losses derived from the electromagnetic model.

$$R_1 = \frac{(-R_i^2 - R_i R_e + 2R_e^2)}{8\pi k R_i (R_i^2 + R_i R_e + R_e^2)} \quad (5)$$

$$R_2 = \frac{(-2R_i^2 + R_i R_e + R_e^2)}{8\pi k R_e (R_i^2 + R_i R_e + R_e^2)} \quad (6)$$

$$R_m = \frac{3(-R_i^3 - 2R_i^2 R_e + 2R_i R_e^2 + R_e^3)}{40\pi k (R_i^2 + R_i R_e + R_e^2)^2} \quad (7)$$

The actuator being surrounded by air, a convective thermal resistance R_c is defined between air and the external and internal actuator's surfaces. For the external surface, R_c is given by:

$$R_c = \frac{1}{4\pi h R_e^2} \quad (8)$$

III. RESULTS AND CONCLUSION

The developed models include two distinct approaches: an electromagnetic model and a thermal model. The electromagnetic model is used to ensure the homogeneity of B_0 and to limit the magnetic field generated by the actuator to less than $3 \mu T$. The thermal model is designed to ensure that the actuator's temperature rise remains below $10^\circ C$ to comply with patient safety requirements. These two models are coupled and integrated into a constrained optimization algorithm. The objective is to minimize the actuator's volume for a given torque calculated by (1) while satisfying both the electromagnetic and thermal constraints. For a torque value of 70 mNm [3], this optimization process resulted in the following actuator dimensions: $R=20\text{mm}$, $e=0.5\text{mm}$, and $J_i=1.2\text{A/mm}^2$. With it, it is the thickness of a coil. The optimization tool used is the single-objective Genetic Algorithm (GA) provided in Matlab® 2023.

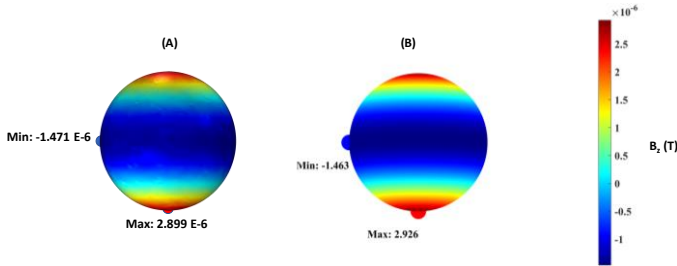


Fig.3. Magnetic Induction B_z on the Surface of a Sphere with Radius R_0 (A: 3D FE Model, B: Analytical Model)

To validate the electromagnetic analytical calculations, a 3D finite element (FE) model was also developed. Since the problem involves an open boundary, the FE model's limit is set far enough to impose a zero-vector potential (typically at $20R$). Additionally, the mesh is dense to accurately estimate the field at R_0 , which significantly increases the FE computation time compared to the analytical model (0.2 s vs. 30 s). Figure 3 shows the distribution of the magnetic flux density B_z on a spherical surface of radius $R_0 = 12 \text{ cm}$ [3]. the agreement between the FE and the analytical models is very good. Moreover, the maximum value computed by the FE method is slightly below $3 \mu T$, aligning with the constraint imposed on the static field B_0 . The analytically and numerically calculated torques are identical and equal to 71 mNm .

To validate the LPTM model, a 3D finite element thermal model was also implemented. A good agreement is observed since the steady state average winding temperature-rise calculated with the LPTM is about $4.7^\circ C$ while the FE model gives $4.67^\circ C$ (Figure 4). The computation time of the FE is about 20 s which is much higher than the LPTM model which lasts 1 s .

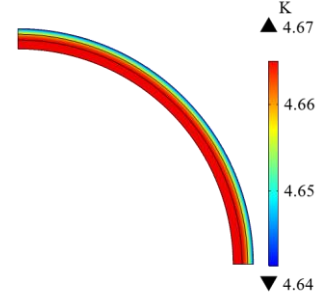


Fig. 4. Steady state temperature-rise distribution using FE analysis.

During a sample extraction, the actuator drives a needle (using a lead screw/nut system not shown here) describing an operating cycle in which the rms current I in the actuator varies with time as follows: Start $0-1 \text{ s}$, $I=10.10$, steady drive $1-7 \text{ s}$, $I=10$, locked in position $7-15 \text{ s}$, $I=5.10$, inverse start $15-16 \text{ s}$, $I=10.10$, inverse steady drive $16-22 \text{ s}$, $I=10$, idle state $22-40 \text{ s}$, $I=0$. I_0 is the rated current of the actuator.

Figure 5 shows the heating of the actuator during 5 cycles. It can be seen that the highest temperature-rise does not exceed $10^\circ C$, making the operation safe in regard to the person's protection against any potential burn. It should be noted that the LPTM and 3D FE models give similar results.

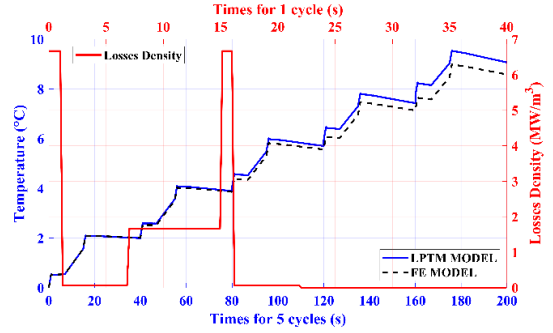


Fig.5. Temperature-rise of the actuator during an operating cycle

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