MRI-Compatible Electromagnetic Spherical Actuator

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Objective – Development of an MRI safe iron free electrical spherical actuator for MR guided surgical interventions.

Findings – The analytical model is significantly faster compared to the FE (finite element) model. The computation time is 0.2 seconds for the electromagnetic analytical model and 30 seconds for the FE model. The optimized actuator does not disturb the B_0 homogeneity. Indeed, the magnetic field generated by the actuator in the imaging area does not exceed 1 ppm of the B_0 field produced by the MRI scanner. Furthermore, the actuator is compact and lightweight compared to its pneumatic counterpart.

Originality – Our MRI compatible actuator uses the B_0 field generated by the MRI scanner as inductor. The design procedure uses a magneto-thermal coupled model associated to genetic algorithms-based optimization

Keywords – Iron-free actuator, Spherical topology, MRI compatibility, Analytical model, Finite elements

1. Introduction

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, notably ultrasonic and pneumatic actuators [2], which have certain drawbacks, such as reduced image quality for the former and significant bulk for the latter.

This work aims to develop a new, more compact, and flexible electromagnetic actuation technology for robot-assisted surgical interventions guided by MRI. We propose the design of an electromagnetic robot capable of operating in an MRI environment. This robot consists of two actuators: a cylindrical actuator [3] and a spherical actuator, which is the focus of this paper. The originality of the proposed synchronous spherical actuator uses the MRI scanner static field as inductor. This makes it very compact, as there is no longer a field armature as in a conventional actuator, while benefiting from an intense inductor magnetic field.

2. ACTUATOR TOPOLOGY AND ANALYTICAL MODELING

The topology of the chosen spherical actuator (Figure 1) uses two quadrature spherical coils powered simultaneously by 2-phase sinusoidal currents to generate a rotating magnetic field. Its interaction with the static magnetic field B_0 generated by the MRI scanner leads to electromagnetic torque production to drive a needle during MRI-guided surgeries.

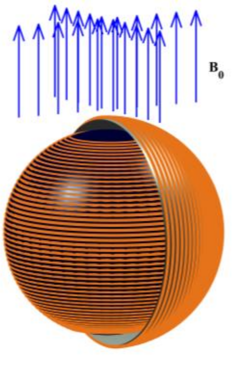

Figure 1 : 3D schematic of spherical actuator in the constant MRI field B_0

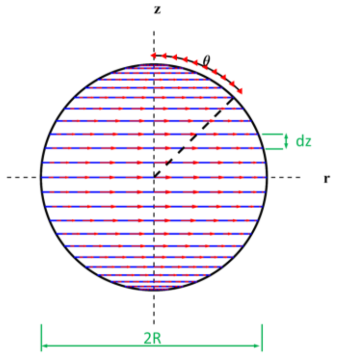

Figure 2 : 2D Axisymmetric Plan of the Spherical Actuator

2.1 Electromagnetic model

A 2D model with axial symmetry is established in spherical coordinates to calculate the field generated by the winding. The total field is determined by superimposing the known inductive field produced by the MRI. A magnetic scalar potential formulation is adopted [4, 5].

Each spherical coil is replaced by an equivalent surface current sheet (Figure 2). Let's note N the total number of turns, so the number of turns in the incremental length dz is $(N/2R)\,dz$. Given that $z = r\,cos\theta$, a differential length dz corresponds to an angular increment $d\theta$ such that $dz = -R\,sin\theta\,d\theta$. Consequently, the number of turns in the differential length $R\,d\theta$, measured along the sphere's periphery, is $(N/2R) sin\theta\,d\theta$. Since each turn carries a current i, the surface current density is:

$$\vec{K} = \frac{Ni}{2R} \sin\theta \vec{u}_{\varphi} \qquad (1)$$

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) .

The magnetic field components are determined using a magnetic scalar potential formulation which leads to the following solution:

$$\vec{H} = \frac{NI\,r}{3R}\left(\cos(\theta)\overrightarrow{u_r} - \sin(\theta)\,\overrightarrow{u_\theta}\right) \quad r<R \qquad (2)$$

$$\vec{H} = \frac{NIR^2}{6\,r^2}\left(2\cos(\theta)\overrightarrow{u_r} + \sin(\theta)\,\overrightarrow{u_\theta}\right) \quad r<R \qquad (3)$$

This computation is used to check the MRI compatibility of the actuator whose magnetic field must not disturb the homogeneity of B_0 in order to ensure a good image quality free of artifacts [6]. In modern MRI, the homogeneity of B_0 is about 1 ppm. Thus, an additional constraint requires that the maximum field due to the actuator, calculated at a certain radius R_0 from the rotation axis, does not exceed 1 ppm of B_0.

The torque produced by the actuator can be easily computed using the Lorenz force which B_0 apply on the current sheet $\vec{K}$. The integration over the sphere's surface of radius R, leads to the following formula of the torque along the x-axis:

$$T = \frac{1}{8}\pi^2 B_0\, J\, (R_2^4 - R_1^4) \qquad (4)$$

3. Results and Conclusion

The developed model is inserted in a constrained optimization algorithm; The goal is to find a set of design parameters that minimize the volume of the actuator while respecting the B_0 homogeneity, the magnetic field created by the actuator should be less than 3 µT). This process resulted in the following actuator's dimensions: $R = 20$ mm, $e = 0.5$ mm and $J = 1.2\ \mathrm{A/mm^2}$. The optimization tool used was the single-objective Genetic Algorithm (GA) provided in Matlab® 2023.

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 $R_0 = 12\ cm$. 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 µT, aligning with the constraint imposed on the static field B_0. The analytically and numerically calculated torques are identical and equal to 71.1 mNm.

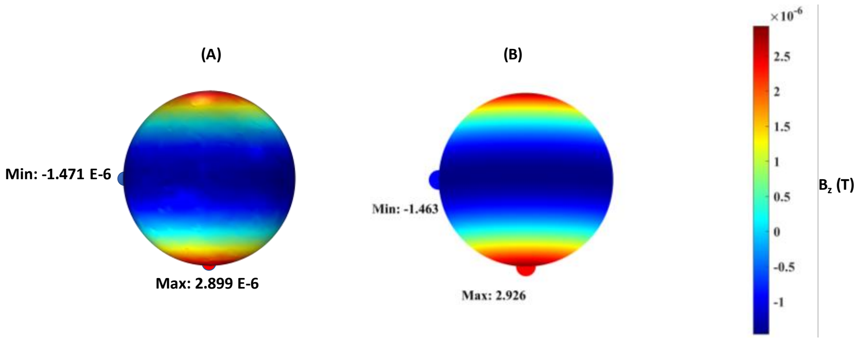

Figure 3 : Magnetic Induction B_z on the Surface of a Sphere with Radius R_0 (A: 3D FE Model, B: Analytical Model)

In the extended version of the paper, we will provide more details on the analytical model, as well as the thermal model and the optimization performed for our actuator. We will also provide further details on the electromagnetic and thermal constraints related to the MRI compatibility of the actuator.

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