Optimization of a Rotor Shape for Spherical Actuator with Magnetically Levitating Rotor to Match Octupole Field Distribution

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ABSTRACT

The use of a reaction sphere as an actuator used by satellite Attitude Control System was proposed over twenty years ago. In principle this concept assumes the use of a single reaction sphere which can be accelerated in any direction instead of a set of reaction wheels. Traditionally the attitude of the satellite can be changed as a result of reaction to the acceleration of the appropriate wheel. As an alternative, the reaction sphere can be accelerated in any direction by a three dimensional (3D) motor. The solution discussed in this work has been proposed and patented by CSEM company. Contrary to conventional ball bearing momentum exchange devices, in this solution the rotor levitates magnetically which results in absence of friction and increase of performance. The sphere can be accelerated in any direction by a three dimensional (3D) motor, making the three axes of the spacecraft controllable by just a single device. The proposed solution of actuator is based on an 8-pole permanent magnet rotor and 20-pole stator with coils (see fig.1).

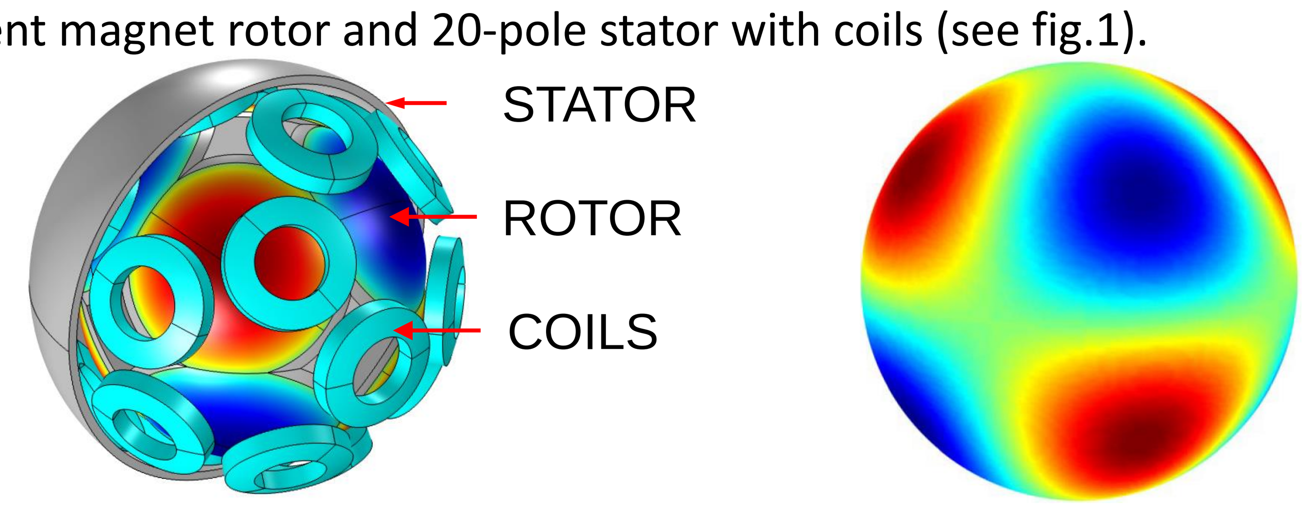


Figure 1 Reaction sphere actuator: on left schematic representation, on right magnetization pattern of the rotor

MODEL AGREEMENT

The goal of the simulation was to find the rotor design which minimize the distortion of the magnetic flux density with respect to the desired fundamental harmonic. The model agreement criterion **d** is introduced as a quantitative evaluation of the global distortion of the magnetic flux density with respect to the spherical harmonic of degree 3 and order 2. This spherical harmonics is the fundamental for the 8-pole rotor in Fig. 1 and has interesting properties that can simplify the control of the reaction sphere [1]. To compute **d**, the radial component of the simulated magnetic flux density $B_r(r_c,\theta,\varphi)$ evaluated at r_c , is decomposed on the basis of spherical harmonics up to a degree N=20 as

$$B_r(rc,\theta,\varphi) = \sum_{n=0}^{N}\sum_{m=-n}^{n} c_n^m Y_n^m(\theta,\varphi)$$

where $Y_n^m(\theta,\varphi)$ is a complex-valued spherical harmonic of degree n and order m, while c_n^m is the decomposition coefficients defined as

$$c_n^m = \int_0^{2\pi}\int_0^{2\pi} B_r(rc,\theta,\varphi)\overline{Y_n^m(\theta,\varphi)}\sin(\theta)\, d\theta d\varphi$$

Therefore, the model agreement criterion d is defined as the ratio between the coefficient relative to the desired harmonic and the sum of the other harmonic coefficients up to the order N as

$$d = |c_3^2| \Big/ \sum_{n=0}^{N}\sum_{m=-n}^{n} |c_n^m|^2$$

Finally, notice that minimizing the magnetic flux density distortion corresponds to maximize the model agreement d ∈ [1,0].

MODEL OF REACTION SPHERE

Permanent magnets are modeled by applying their linear constitutive relation $B = \mu_0\mu_r H + B_r$, where B and H are the magnetic flux density and the magnetic field, respectively; The relative magnetic permeability μ_r is fixed to 1.05 while the norm of the remanent magnetic flux density Br was equal to 1.15 or 1.4 T. Finally μ_0 is the vacuum permeability. The back-iron and stator shield are modeled using the linear B-H relation, with the relative magnetic permeability equal to 1000 for material with high permeability (eg. electrical steel) or 1 for material with low permeability (eg. some kind of stainless steel or plastic). No saturation effects were taken into account at first stage of the design.

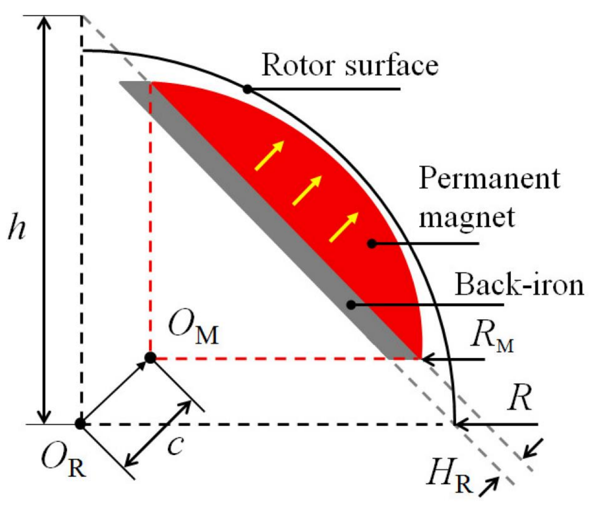


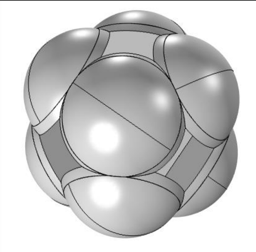
Figure 2 Profile of a rotor pole

During optimization of the rotor structure, the following parameters were optimized (see fig.2):

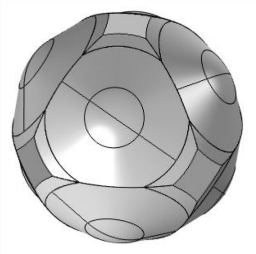
RM – the radius of permanent magnets poles;
c – the eccentricity between rotor center OR and the pole center OM;
h – the height of the truncated octahedron structure;
HR – the back-iron thickness;

Based on parameters RM, c, h, HR we prepared rotor configurations R01 to R05 with spherical poles. Moreover, we considered five more rotors configuration which are developed version of rotors R03, R04 and R05 with conical shape of rotor poles (see below).

R05



R05Kmin



	RM	c	h	HR	M_B_I	M_PM	Mrot
R01	50	5	73.7	2.8	0.566	1.4045	2.502
R02	45	10	72.4	3.1	0.5905	1.401	2.508
R03	40	15	70.7	3.4	0.602	1.4065	2.507
R04	35	20	68.6	3.9	0.627	1.405	2.509
R05	30	25	65.7	4.6	0.647	1.406	2.509

	RM	c	h	HR	M_B_I	M_PM	Mrot
R03K	40	15	70.7	3.15	0.614	1.463	2.495
R03Kmm	40	15	71.7	2.9	0.591	1.408	2.439
R03Kmin	40	15	72.5	3	0.622	1.344	2.417
R04Kmin	35	20	72.5	3	0.619	1.258	2.348
R05Kmin	30	25	72.5	3	0.617	1.183	2.288

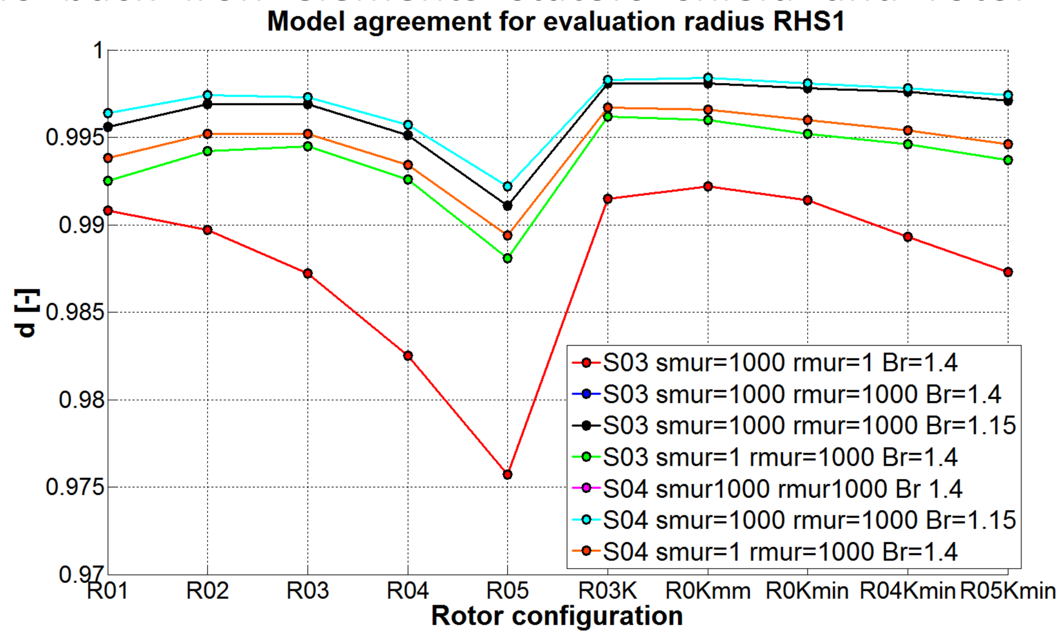
RESULTS

During simulations the influence of stator shield thickness and permeability on magnetic field distribution were also investigated. The two stator configurations were considered:

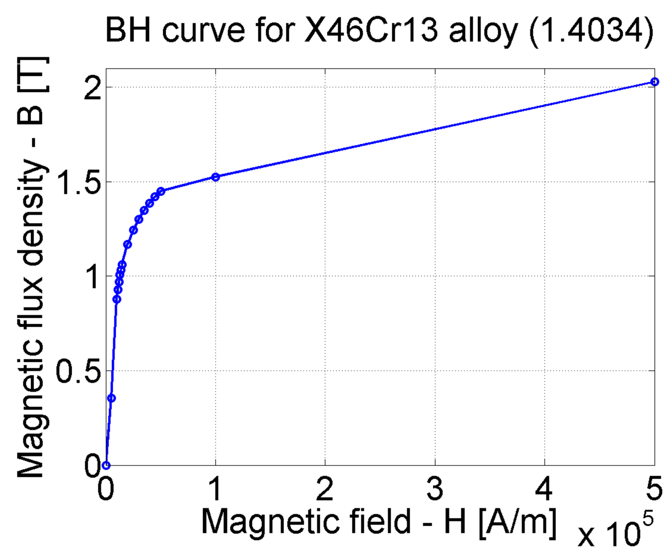
S03 – coil height TW=6mm and outside shield thickness TB=2.8mm
S04 – coil height TW=8mm and outside shield thickness TB=2.1mm

Studied combinations of rotors back iron elements stators shield and rotor

Stator S03	Stator S04
Stator mur=1000 Rotor mur=1 Magnet Br 1.4	-
Stator mur=1000 Rotor mur=1000 Magnet Br 1.4	Stator mur=1000 Rotor mur=1000 Magnet Br 1.4 T
Stator mur=1000 Rotor mur=1000 Magnet Br 1.15	Stator mur=1000 Rotor mur=1000 Magnet Br 1.15 T
Stator mur=1 Rotor mur=1000 Magnet Br 1.4	Stator mur=1 Rotor mur=1000 Magnet Br 1.4 T



The next analyses were focused on rotors R03, R03Kmin and R03Kmm. For these rotors saturation effects were also checked. The material of back iron elements was implemented in COMSOL Multiphysics as an interpolation function of the B-H curve of the steel X46Cr13; see fig.3.



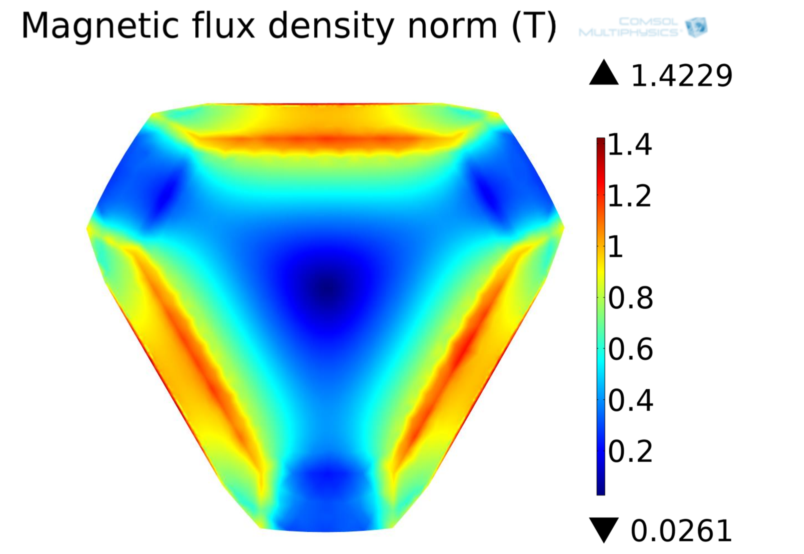


Figure 3 B-H curve for steel X46Cr13 (left); View on back-iron element with 7mm thickness (right)

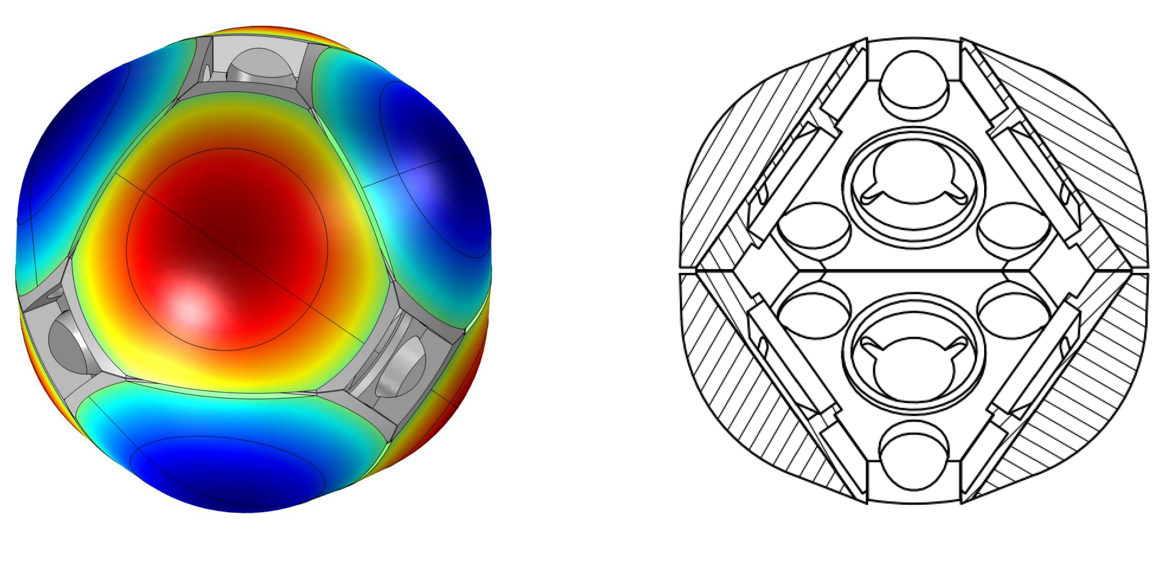


Figure 4 Final rotor design for Reaction Sphere actuator

In this work we presented the design optimization of a permanent magnet spherical rotor for the Reaction Sphere actuator. Given a set of specifications on the mass budget, the outer radius and minimum forces and torques generated in the actuator the rotor design optimization focused on minimizing the distortion of the magnetic flux density with respect to the desired fundamental harmonic. The final rotor consists of 8 bulk permanent magnet poles with truncated conical shape that are parallel magnetized and positioned on the back-iron structure with dimension presented in figure 4.

REFERENCES

[1] - Rossini, Leopoldo, et al. "Force and torque analytical models of a reaction sphere actuator based on spherical harmonic rotation and decomposition." (2012): 1-13.
[2] - Rossini, L., et al. "Rotor design optimization for a reaction sphere actuator." Electrical Machines and Systems (ICEMS), 2012 15th International Conference on. IEEE, 2012.

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