Topology Optimization Method for Nuclear Magnetic Resonance Logging tool Magnetic and Soft magnetic Design

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Introduction： Nuclear magnetic resonance logging is an important part of petroleum exploration, and the design of the NMR probe magnet, antenna, and soft magnetic material is related to the accuracy of downhole reservoir detection. Traditional probe design is often based on empirical structures, which reduces the accuracy of matching the probe magnet and antenna, increases the cost of manual optimization (time and effort).

Methods： This study uses the Finite Element Method to effectively solve the B_0 and B_1 magnetic fields . In order to optimize the antenna and magnetic field at the same time, two magnetic fields are set and the design variables are derived separately by the chain rule:

$$\iint_{\Omega} V\left(\frac{\partial A_Z}{\partial_X}\frac{\partial A_Z}{\partial_X}+\frac{\partial A_Z}{\partial_X}\frac{\partial A_Z}{\partial_X}\right)dxdy=\iint_{\Omega} V\left(\frac{\partial A_Z}{\partial_X}\frac{\partial A_Z}{\partial_X}+\frac{\partial A_Z}{\partial_X}\frac{\partial A_Z}{\partial_X}\right)dxdy+\iint_{\Omega} J_Z N dxdy$$

N is the basis function, and A_Z is the magnetic vector potential.

We have divided the construction of magnets, antennas, soft magnetics, topology optimization and air domain into separate parts. The objective function, point distribution and constraints are as follows:

$Find: \rho = (\rho_1, \rho_2, \rho_N)$

$$Maximize: \phi = \sum_{i=1}^{100} B_{0,\ i}^2 \bullet (B_{1m}/I)$$

$Subject\ to: 0 \le \rho_e \le 1$

The density interpolation model of SIMP interpolation function is used for density interpolation. The finite element material interpolation function is:

$$\mu(\rho_e) = \mu_0 + \theta_p \bullet (\mu_i \bullet \mu_0 - \mu_0)$$

μ_0 is the magnetic permeability of air, and μ_i is the permeability of soft magnetic material.

The model is iteratively solved using the moving asymptote method (MMA) based on gradient descent.

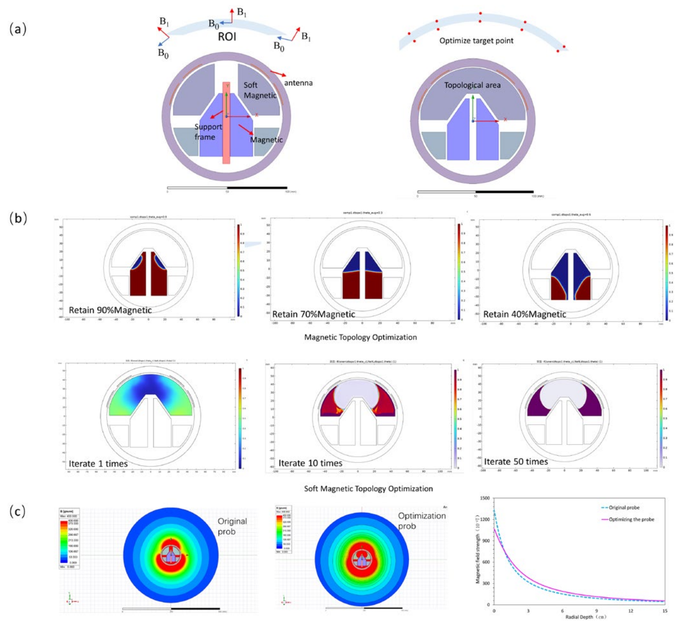

Fig. 1: (a) illustrates the optimization objective and the optimization domain. (b) shows the topology-based optimization of the magnet and the soft magnetic material. (c) presents the optimization results.

Results and discussion： The magnet volume is reduced by 10%, 30%, and 60%, the resulting magnetic field strength decreases accordingly. To generate the maximum magnetic field, the entire magnet volume is selected as the primary magnet. The soft magnetic material, after topology optimization, exhibits a horn-shaped structure. The sensitive region is located 5–7 cm outside the magnet. and it can generate a static magnetic field with an intensity of 114.6 ~ 157.8G and a gradient of 273.0 ~165 G/cm in the distal ROI as illustrated in **fig（c）**.

References: [1] Gregor, Sci. Rep. （2022）.
[2] Deaton, Struct Multidiscip O. (2014).