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Design and simulation of superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)

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ABSTRACT

Lorentz Force Electrical Impedance Tomography (LFEIT) is a hybrid diagnostic scanner with strong capability for biological imaging, particularly in cancer and haemorrhages detection. This paper presents the design and simulation of a novel combination: a superconducting magnet together with LFEIT system. Superconducting magnets can generate magnetic field with high intensity and homogeneity, which could significantly enhance the imaging performance. The modelling of superconducting magnets was carried out using Finite Element Method (FEM) package, COMSOL Multiphysics, which was based on Partial Differential Equation (PDE) model with *H*-formulation coupling *B*-dependent critical current density and bulk approximation. The mathematical model for LFEIT system was built based on the theory of magneto-acoustic effect. The magnetic field properties from magnet design were imported into the LFEIT model. The basic imaging of electrical signal was developed using MATLAB codes. The LFEIT model simulated two samples located in three different magnetic fields with varying magnetic strength and homogeneity.

1. Introduction

Lorentz Force Electrical Impedance Tomography (LFEIT), also known as Hall Effect imaging (HEI) or Magneto-Acousto-Electric Tomography (MAET), is one of the most promising hybrid portable device with burgeoning potential for cancer and internal haemorrhages detection [1–3]. In contrast to ultrasonic imaging technology's disadvantage in distinguishing soft tissues as acoustic impedance varies by less than 10% among muscle and blood, LFEIT show its powerful capability in providing information about the pathological and physiological condition of tissue because electrical impedance varies widely among soft tissue types and pathological states [4]. Other than carcinomas, tissues under conditions in haemorrhage or ischemia are able to exhibit huge difference in electrical properties because most body fluid and blood have fairly different permittivity and conductivity compared to other soft tissues [5]. Fig. 1 presents the schematic of a superconducting Lorentz Force Electrical Impedance Tomography (LFEIT). LFEIT is on the basis of electrical signal measurements arising when an ultrasound wave propagates through a conductive medium, which is vertically subjected to a magnetic field [1]. The magnitude of electrical signal is proportional to the strength of the magnetic field and the pressure of ultrasound wave [1].

In the 1990 s, Hall Effect imaging (HEI) was developed by [3]. HEI use the Lorentz Force based coupling mechanism with ultrasound. HEI technology detects the Hall voltages using surface electrodes on the tested specimen, where these voltages are induced by using ultrasound to cause localised mechanical vibrations in a conductive tissue specimen located in a static magnetic field [3]. The spatial imaging of HEI is very close to ultrasound imaging, which is mainly determined by the bandwidth and central frequency of the ultrasound packets generated [1,3]. The method of Magneto-acoustic tomography with magnetic induction (MAT-MI) was proposed by He and colleagues, which has made the breakthrough to solve the shielding effect problem existed in other hybrid bio-conductivity imaging techniques [2]. Unlike HEI, MAT-MI use Lorentz force to induce eddy current to produce ultrasound vibrations which can be detected by using ultrasound transducers (receiving mode) placed around the specimen. Then, the recorded ultrasound signals are utilised to reconstruct the conductivity distribution of the biological sample [2,6]. In 2013, an experimental Lorentz Force Electrical Impedance Tomography (LFEIT) was developed by Grasland-Mongrain et al. [1]. Two

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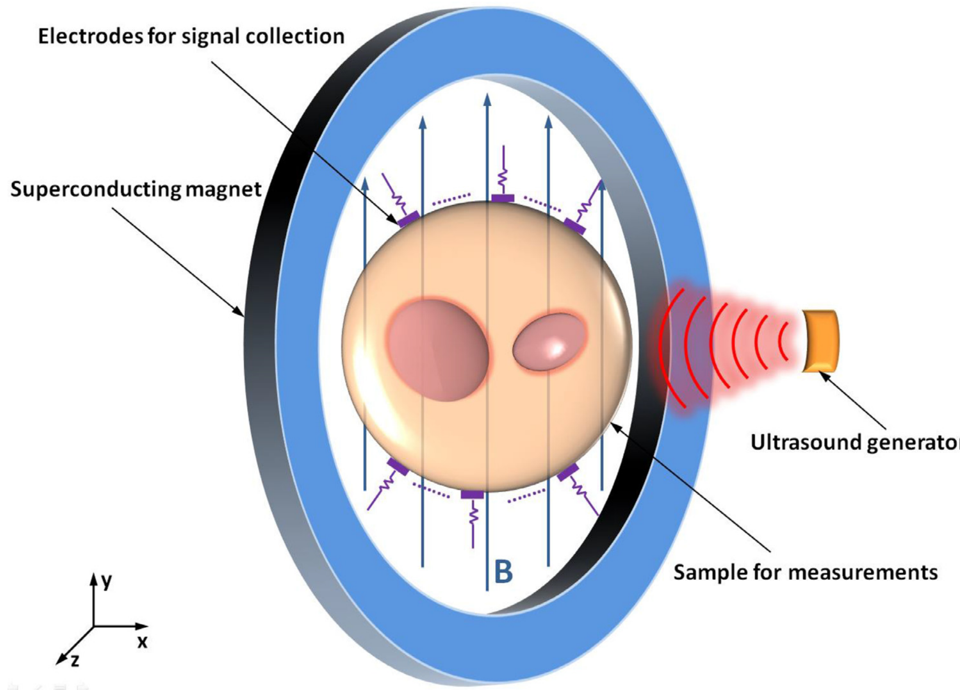

Fig. 1. Schematic of superconducting Lorentz Force Electrical Impedance Tomography (LFEIT).

specimens were chosen: a gelatin phantom and a beef sample, which were successively fixed into a 0.3 T magnetic field B_0 and sonicated with an ultrasonic transducer emitting 500 kHz bursts [1]. The results reveal that LFEIT has the potential to reach the spatial resolution of the ultrasound, and realize the detection of small inhomogeneities of soft tissue such as tumorous tissues.

As the magnetic field is crucial for generating the final electrical signal of LFEIT, authors have tried a novel combination of superconducting magnet with LFEIT system. The reason is that superconducting magnets can generate magnetic field with high intensity and homogeneity [7], which could efficiently enhance the electrical signal induced from sample thus improve the sound-to-noise ratio (SNR), particularly for a large scale full-body LFEIT. To the best of our knowledge, currently there is no research on design of LFEIT equipped with superconducting magnet. This paper presents the simulation of superconducting LFEIT system, which include the modelling of superconducting magnet using the FEM software COMSOL Multiphysics, coupled with the mathematical model of magneto-acoustic effect from LFEIT.

2. Modelling of superconducting magnet

The modelling of superconducting magnets was carried out on the basis of our previous work [8]. As the superconducting Helmholtz Pair, the conventional magnet structure for MRI, occupies a large space due to specific arrangement for Helmholtz coils location, the portability of LFEIT like equipping into general ambulances is difficult to realize [8]. Therefore, authors proposed superconducting magnets with thin geometry using the Halbach Array configuration [8,9]. Superconducting coils were used to build an electromagnet operating below its critical temperature, which was able to generate a proper homogenous magnetic field. Fig. 2 presents the concept of superconducting Halbach Array magnet for 8 coils (each coil has 90° phase change) and 12 coils (each coil has 60° phase change).

COMSOL Multiphysics was chosen as the platform for the modelling of superconducting magnet, which was based on Partial Differential Equation (PDE) model with 2D H-formulation. The general form of H-formulation is [10]:

$$\mu_0\mu_r\frac{\partial H}{\partial t} + \nabla \times (\rho\nabla \times H) = 0 \tag{1}$$

where H is the magnetic field intensity, μ_0 is the permeability of free space, μ_r is the relative permeability, ρ is the resistivity. Here, B-dependent critical current density and bulk approximation were also coupled into the modelling of superconducting magnet [11]:

$$J_c(B) = \frac{J_0}{\left(1 + \sqrt{\frac{k^2 {B_{para}}^2 + {B_{perp}}^2}{B_0}}\right)} \tag{2}$$

$$NI_t = \int J_t dA \tag{3}$$

where J is the current density, B is the magnetic flux density. Eq. (2) reveals that J_c is reduced in the perpendicular and parallel magnetic field. J_0 is the critical current at 77 K within zero magnetic field. The parameters used in Eq. (2) are $B_0 = 0.426$ and $k = 0.186$ presented in literature. In the magnet design, multiple tapes with layers of coated conductor were represented by continuous area bulk approximation to improve model simulation speed. Eq. (3) indicates the multiplication of the transport current I_t in each tape and the number of turns N is identical to the integration of current density J_t inside bulk approximation with cross-section area A.

The 1.2 cm YBCO tape manufactured by SuperPower®, with critical 300 A at 77 K, was simulated as the coil material for superconducting Halbach Array. Fig. 3 presents the mesh for superconducting Halbach Array designs with (a) 8 HTS coils and (b) 12 HTS coils. Stacks of coils are represented by bulk approximation, and each pair bulk cross-sections represent 2000 turns (4×500 turns of a single layer rectangular coil) YBCO coils. As shown in Fig. 3, air was set in the ring centre and coils were fixed by the non-magnetic Halbach Array frame. A DC current 120 A was applied to each coil. Without changing the total amount of superconductor, Halbach Array configuration can use different numbers of coils, which can be realised by shrinking each coil's size with increasing number of coils (from 8 coils to 12 coils). The specification for