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Magnetic nanostructures as amplifiers of transverse fields in magnetic resonance

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Abstract

We introduce the concept of amplifying the transverse magnetic fields produced and/or detected with inductive coils in magnetic resonance settings by using the reversible transverse susceptibility properties of magnetic nanostructures. First, we describe the theoretical formalism of magnetic flux amplification through the coil in the presence of a large perpendicular DC magnetic field (typical of magnetic resonance systems) achieved through the singularity in the reversible transverse susceptibility in anisotropic single domain magnetic nanoparticles. We experimentally demonstrate the concept of transverse magnetic flux amplification in an inductive coil system using oriented nanoparticles with uni-axial magnetic anisotropy. We also propose a composite ferromagnetic/anti-ferromagnetic core/shell nanostructure system with uni-directional magnetic anisotropy that, in principle, provides maximal transverse magnetic flux amplification.

Keywords: Magnetic resonance; Signal-to-noise ratio; Magnetic nanostructures; Magnetic resonance microscopy; Magnetic resonance spectroscopy; Magnetic nanoparticles; Magnetic susceptibility

1. Introduction

Magnetic resonance spectroscopic techniques are invaluable in analytical chemistry, biology, and materials science, while the incorporation of magnetic field gradients into the magnetic resonance settings has allowed magnetic resonance imaging and microscopy [1–4] to become widespread, especially in medical diagnostics [5]. Both spectroscopic and imaging applications of magnetic resonance have traditionally suffered from the low signal-to-noise ratio due to the weak nuclear magnetic moment of the proton and the low fractional polarization, even in large magnetic fields at room temperature [6]. The challenge of low signal-to-noise ratio in magnetic resonance has been historically alleviated by using the ever higher magnetic fields, better amplifier technology, and application of more efficient pulse sequences and signal processing techniques, among others.

Despite these advances, the sensitivity limits in magnetic resonance detection technology are still being intensively pursued, with many of the detection techniques being quite different from the traditional inductive methods. These include force detection [7–10], direct transfer of angular momentum [11–14] and energy [15,16] from the spin population in magnetic resonance using micro-mechanical cantilevers, flux-detection class of magnetic resonance sensing schemes such as superconducting quantum interference devices (SQUID) [17,18], Hall sensors [19,20], and superconducting resonators [21], as well as optical methods [22–24]. Although further advances in these experimental methods are likely to continue, it is an intriguing fact that the

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inductive coil technology has remained the main workhorse in magnetic resonance systems, both in spectroscopic and imaging settings. It is to the further improvements in this conventional magnetic resonance technology that we address the ideas and arguments in the present article.

The essential elements in a conventional high-field (~0.1–10 T) magnetic resonance instrument that directly influence and interact with the sample are (a) the DC magnetic field source (electro-magnet, permanent magnet, or superconducting magnet) for applying a large polarizing DC magnetic field along the *z*-axis, (b) the radio-frequency transmitter coil for generating time-dependent magnetic fields perpendicular to the DC magnetic field, (c) the radio-frequency receiver coil for detecting the weak time-dependent sample generated magnetic fields which are also perpendicular to the DC magnetic field, (d) shim coils for improving the field homogeneity, and for the imaging case, (e) current carrying gradient coils for generating time-dependent and spatially varying magnetic fields [25]. This list attests to the importance of current carrying structures in magnetic resonance settings, whether they are in the shape of solenoids, saddles, or birdcages. These current carrying structures are so valuable in magnetic resonance instruments because they are able to generate as well as detect time-dependent, spatially uniform or non-uniform magnetic fields despite the presence of the large perpendicular DC polarizing magnetic field. This independence and immunity of the current carrying structures to the perpendicular large external DC magnetic field is a true secret to their success in magnetic resonance applications.

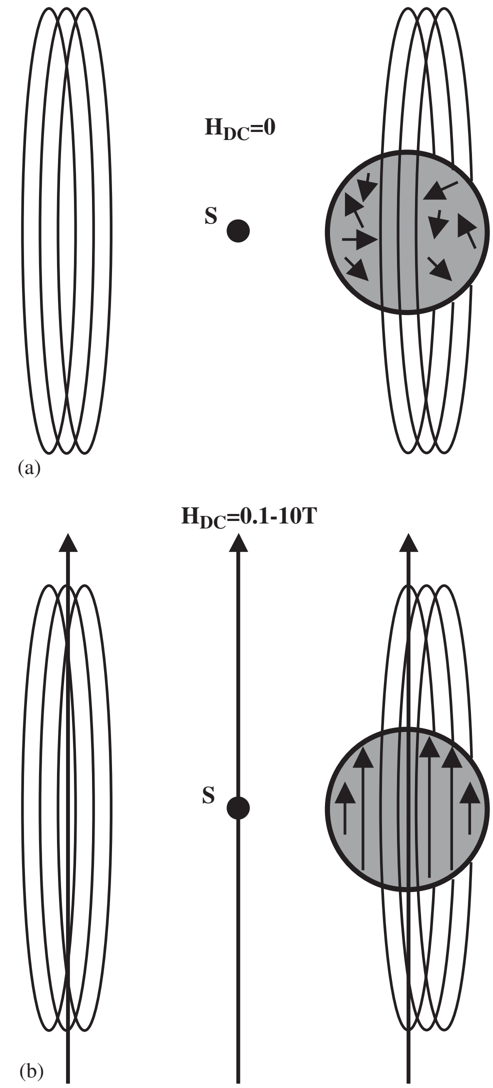

Fig. 1. (a) Two solenoids with equal dimensions and equal number of turns are equally distanced from the sample location S. For the same applied alternating current through both solenoids in zero external magnetic field, the alternating magnetic field along the *x*-axis at point S produced by the solenoid filled with a soft ferromagnet on the right will be larger than the alternating magnetic field along the *x*-axis produced by the air-core solenoid on the left. However, in a typical magnetic resonance experiment, as shown in (b), the entire region is under the influence of a large external polarizing DC magnetic field. Both solenoids will, for the same alternating current, produce the same alternating magnetic field along the *x*-axis, since the soft ferromagnetic core of the solenoid on the right is saturated.

2. Air-core solenoids vs. electro-magnets

It has been known for over a century that significant amplification of the magnetic field produced by a solenoid can be achieved if a soft ferromagnetic material, such as iron, is inserted into the coil structure [26]. In this article, we address the possibility of achieving similar amplification of the generated and/or detected alternating magnetic fields in conditions typical of magnetic resonance settings where a large DC magnetic field is commonly applied to the entire region encompassing the sample, RF transmitter, RF detector, and gradient coil. Fig. 1 illustrates the basic challenge. Consider first the situation of Fig. 1(a) where two solenoids with identical dimensions and number of turns are positioned so that they are equally distanced from the sample location S. The external DC magnetic field present over the entire region is initially zero. The solenoid on the left is air-filled, while the solenoid on the right is modified by insertion of a soft ferromagnetic core, assumed for simplicity to be spherical in shape. For the same applied alternating electric current through both solenoids, the alternating magnetic field along the *x*-axis at point S produced by the ferromagnet-filled solenoid on the right will be significantly larger than the alternating magnetic field along the *x*-axis produced by the air-core solenoid on the left, due to basic electro-magnet effect. However, in a typical magnetic resonance experiment, the entire region is under the influence of a large (0.1–10 T) external