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RF Pulse Response and NMR Signal Enhancement in Ferromagnets

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Abstract: Ferromagnets are very important class of materials having wide variety of technological applications as memory elements, solid state switches etc. The overall property is graetly influenced by local structure, dynamics and the processing variables of the material. The local structure and dynamics can be easily studied using Nuclear Magnetic Resonance (NMR).The method of NMR essentially involves placing the sample in an externally applied static magnetic field and then applying a radio frequency (rf) field at right angles. The local dynamics in ferromagnets may be studied using the so called zero field NMR spectroscopy where the strong field already present in the material give rise to splitting of the Zeeman levels. Excitations among these levels are achieved by applying radio frequency (rf) field of appropriate frequency and magnitude. The applied rf field and the observed Free Induction Decay (FID) signal get highly enhanced in ferromagnets. This enhancement is up to different extents for nuclei in domains and domain-walls. The enhancement and variation of NMR Free Induction Decay (FID) signal amplitude with the strength of the applied radio frequency field has been explained by Stearns by invoking a model where it has been assumed that the domain-walls oscillate like the drumhead when subjected to NMR rf pulses.In this paper an alternative model is proposed and an attempt has been made to calculate the FID signal by taking into consideration the spiral orientation of the magnetization when one moves from one domain to the adjacent domain. We concentrate on spin I=1/2 system for simplicity as no quadrupolar effects are then involved.
Keywords: NMR, FID, Ferromagnets, RF Pulse.

1. Introduction

The local dynamics in ferromagnets may be studied using the so-called zero field NMR spectroscopy where strong fields already present in the material give rise to the splitting of the Zeeman levels. Ferromagnets may involve nuclei having spins I=1/2 (^{57}Fe), I=3/2 (^{61}Ni), I=5/2 (^{55}Mn), I=7/2 (^{59}Co), I=9/2(^{93}Nb), etc, which will have two, four, six, eight and ten Zeeman levels. Calculations for signals would essentially involve two, four, six, eight and ten coupled differential equations (rate equations). These calculations may be carried out by solving these coupled equations or by resorting to density matrix method. Excitations among the Zeeman levels are achieved by applying radio frequency (rf) field H_1 of appropriate frequency and magnitude. The applied rf field and the observed Free Induction Decay (FID) signal get highly enhanced[1] in ferromagnets as explained below.

When an rf field strength B_1 is applied to a sample of magnetic material, the nuclei feel a field augmented by a factor η. This quantity is known as the NMR enhancement factor and has different values in domains and in the domain-walls. Assuming that inside the domains the atomic magnetic moments feel an anisotropy field B_a along the Z direction, a perpendicular rf field B_1 displaces the magnetization from its equilibrium position. The appearance of a perpendicular component of the atomic moment leads to a hyperfine field component in the same direction of B_1, since the hyperfine field B_{hf} is approximately proportional to magnetization M. From Fig. 1, one can see that

$$\frac{B^{1}_{hf}}{B_1} = \frac{B^{1}_{hf}}{B_a} = \frac{B_{hf}}{B_a},$$

which is the expression of the enhancement factor in the domains.

$$\eta_d = \frac{B_{hf}}{B_a}, \tag{1}$$

In the presence of an external field B_0, also parallel to Z, the enhancement factor becomes

$$\eta_d = \frac{B_{hf}}{B_a + B_0}, \tag{2}$$

inside the domain wall, the field B_1 is amplified by the factor η_w, which is much larger than η_d. This amplification effect can be understood as follows. The field B_1 displaces the wall, favouring the growth of the domains with the direction of the magnetization close to the direction of B_1. This displacement induces a rotation of the magnetization inside the wall, which

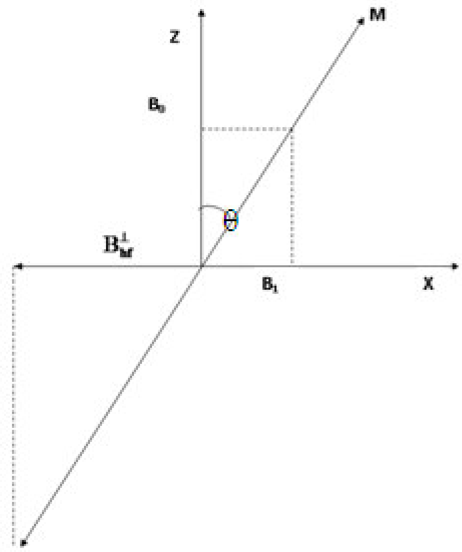

Fig.1 Amplification mechanism of the rf field inside a domain, the magnetic moment is turned by an angle θ, and the transverse component of the applied field becomes $B_{hf}^{\perp}$ much larger than B_1.

leads to the appearance of components of the hyperfine field along B_1, that add to this rf field, this is the mechanism of enhancement in the walls. This enhancement depends on the position *x* inside the wall. For the nuclei at the domain wall centre the factor η_w reaches a maximum. The enhancement factor η_w is proportional to the displacement of the domain-wall, for small values of the displacement. This enhancement and variation of NMR Free Induction Decay (FID) signal amplitude with the strength of the applied radio frequency field has been explained by Stearns [2] by invoking a model where it has been assumed that the domain-walls in a ferromagnet such as Fe (Spin I=1/2) oscillate like the drumhead when subjected to NMR rf pulses. Based on this Stearns[2], derived an expression for FID which explained the experimental data very well.

2. The Model

A schematic diagram of the 180° domain-domain-wall structure is shown in Fig. 2. Consider a 180 ° domain wall of thickness *l*. The magnetization has spiral orientation as shown in Fig. 2. Divide the wall in N slices for easy visualization. A field applied in X-direction will tend to tilt the magnetization in the slice towards X. It means that the slice 1 would become like 2 and slice 2 like 3 and so on as far as oscillation of the magnetization is concerned. The arrows in the slices indicate the orientation of individual magnetization M of the slices. The angles θ_1, θ_2, θ_3... are the tilt angles of these magnetizations with respect to the direction of the magnetization of the wall (Z). Angle of tilt of the nth slice is $\theta_1+n(\pi/2)/l$.

If the nth slice is located at distance x from the beginning of the wall then angle of M of slice at x is equal to $\theta_1+(\pi/l)x$. These are the static orientations of the slices. A slice at a distance x having M at an angle $\theta= \theta_1+(\pi/l)x$ indicates that presence of a field H_2 along X may be visualized.

Now $\tan\theta = H_2/H_0$, where H_0 is the field due to domains. Now another field H_1 is applied along X. The slice at x now reorients itself to a new direction θ'given by

(3) $$\tan\theta' = \frac{H_2+H_1}{H_0} = \frac{H_0\tan\theta + H_1}{H_0},$$

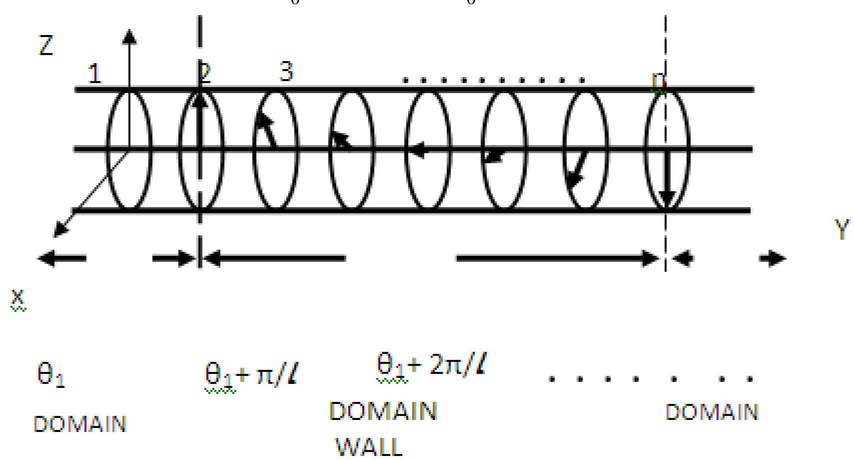

Fig. 2 A Schematic diagram of 180^0 domain-domain-wall structure

DOMAIN

Change in direction is given by angle $\delta\theta = \theta' - \theta$. Therefore

$$\tan\delta\theta = \frac{H_1}{H_0 + \left(H_0 \tan\theta + H_1\right)\tan\theta'}. \tag{4}$$

Assuming δθ to be small, we get

$$\delta\theta \approx \frac{H_1}{H_0 + H_0 \tan^2\left(\frac{\pi}{l}x\right) + H_1 \tan\left(\frac{\pi}{l}x\right)} = \frac{\frac{H_1}{Ho}}{1 + {x_1}^2 + \frac{H1}{Ho}x_1}, \tag{5}$$

where $x_1 = \tan(\pi / l)x$. Assuming that the FID i.e. signal induced in the coil is proportional to the component of magnetization tilted towards the H_1 field i.e. signal enhancement is proportional to δθ, the signal after a rf pulse of width τ and field strength B_1 can be obtained following Stearns [2] as

$$Signal \propto \int_{x_1=0}^{\infty}\int_{\eta=0}^{\pi} \sin\left(\alpha_0 f(x_1)\cos\eta\right) f(x_1)\cos\eta \sin\eta \, d\eta \, dx_1, \tag{6}$$

where it has been assumed that the enhancement is proportional to the change in orientation of magnetization of each slice when subjected to rf field. In equation (6) integration over η has been taken to include contribution to the signal from all the slices as the crystallites in a powdered sample are distributed randomly with respect to the direction of applied rf field.

3. Results

The signal given by equation (6) is evaluated using MATHEMATICA program and is shown in Fig. 4 as function of α_0. It is noted that our result obtained using above arguments is similar to the curve (b) of Fig.3 obtained by Stearns [2]. It is interesting to note that the simple model proposed here without assuming any drumhead type of motion, predicts a behaviour which tends towards the experimentally observed data, although it does not completely predict the correct behaviour (A preliminary report based on this work was presented earlier[5]). Further modifications are necessary on this model. We believe that oscillatory motion of the tilted magnetization in the domain wall under the influence of rf field would yield the correct behaviour.

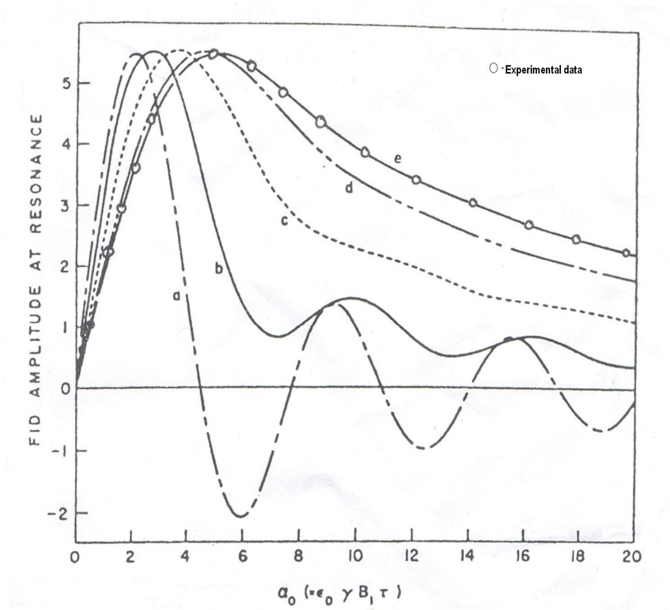

Fig.3 Experimental and Calculated curves of FID amplitude at resonance as a function of the maximum turning angle α_0 [2].

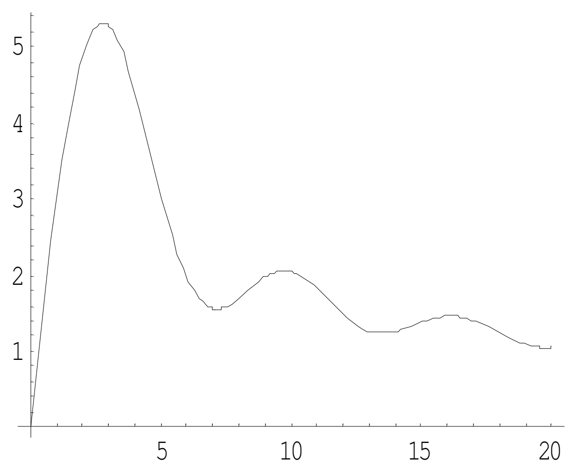

Fig.4 Plot of the signal given by equation (6) evaluated using MATHEMATICA Program.

4. Conclusions

The existing model for ferromagnets which is based on the assumption that the domain walls vibrate like drumheads when rf pulses are applied, was reviewed and attempt was made to answer the question that why the walls should vibrate like drumheads. For this more physically appealing alternative model for domain wall dynamics was proposed. Based on the fact that the magnetization undergoes a spiral orientation as one moves from one domain to the other through the domain wall, it was assumed in the proposed model that if we treat the wall to be made of thin slices then magnetization in any slice would reorient itself easily between the two adjacent slices, one previous one and the other the next one. Expression for the Free Induction Decay (FID) amplitude was derived. It was found that our result partly agrees with those obtained from the existing model. Further work on improving this model is in progress.

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