THEORETICAL AND EXPERIMENTAL APPROACH TO SPIN DYNAMICS IN THIN MAGNETIC FILMS.

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The Landau-Lifshitz (L-L) equation describing the time dependence of the magnetisation vector is numerically integrated fully without any simplifying assumptions in the time domain and the magnetisation time series obtained is Fourier transformed (FFT) to yield the permeability spectrum up to 10 GHz. The non linear results are compared to the experimental results obtained on magnetic amorphous thin films of Co-Zr, Co-Zr-Re. We analyse our results with the frequency response obtained directly from the Landau-Lifshitz equation as well as with the second order Gilbert frequency response.

I. INTRODUCTION

The development of high-density information storage involves developments in new materials for recording heads and recording media. The required properties for recording heads are high saturation magnetisation $M_s$, low coercivity $H_c$, low magnetostriction coefficient $\lambda$ and high permeability $\mu$ over a broad frequency range (typically several hundred MHz).

Thin films such as Co-M1-M2, (M1, M2 = Zr, Nb, Re...), FeTaN and FeZrN have been investigated in view of these applications. These materials belong to a new class of ultrasoft films used in high density magnetic recording devices. In order to improve the data read-out in magnetic recording heads the frequency behaviour of the permeability should stay large at high frequencies. At low frequencies, when the exciting field is applied along the easy axis, the initial permeability, due mainly to motion of magnetic walls, is large and rolls off at about a few tens of kHz. On the other hand, when the exciting field is applied perpendicular to the easy axis, the permeability is generally lower and due to spin rotation. In this case, the roll-off frequency may approach a few hundreds MHz.

Previous studies agree with the fact the Landau-Lifshitz equation describes successfully the ferromagnetic behaviour of the material from the resonance frequency and linewidth points of view.

Since the Landau-Lifshitz equation has been used in the study of many magnetic systems and more recently in thin magnetic films, we applied it to Co-Zr, Co-Zr-Re thin amorphous films.

We perform our studies experimentaly in the [10 MHz, 10 GHz] frequency range with a special broadband measurement technique that we have developed previously.

Usually, the Landau-Lifshitz equation, is linearised and Fourier transformed in order to extract the complex magnetic permeability as a function of frequency. Instead, we take the fully non linear equation and treat it with time domain integration methods.

We develop a new accurate and stable numerical time integration technique over long durations (in order to have accurate results in the frequency domain) and perform the Fourier transform (FFT) directly on the calculated magnetisation time series. These results are compared with the measurement and agree to some extent with the previous theoretical results obtained with the linearisation approach. Nevertheless non linear effects are visible in the frequency range we consider.

This paper is organised as follows. In section 2 we present our experimental and simulation results and discuss the effects of some physical parameters on the behaviour of the permeability. The experimental results are compared to the linear and non linear responses and section 3 contains our conclusions.
II. EXPERIMENTAL AND SIMULATION RESULTS

The Landau-Lifshitz equation is:

\[
\frac{d\mathbf{M}}{dt} = \gamma (\mathbf{M} \times \mathbf{H}) - \alpha \gamma \frac{\mathbf{M} \times (\mathbf{M} \times \mathbf{H})}{|\mathbf{M}|}
\]

(1)

where \( \mathbf{M} \) is the magnetisation vector, \( \mathbf{H} \) the effective field, \( \gamma \) the gyromagnetic ratio (in our case \( \gamma = 2.2 \times 10^{5} \text{mA}^{-1}.\text{s}^{-1} \)) and \( \alpha \) the damping parameter.

The effective field is:

\[
\mathbf{H} = H_k \mathbf{x} + h_y \cos(\omega t) \mathbf{y} - M_z \mathbf{z}
\]

(2)

where \( H_k \) is the anisotropy field and \( M_z \) is the demagnetisation field.

The frequency permeability response \( \mu(\omega) = \mu'(\omega) - j \mu''(\omega) \) might be calculated directly from the L-L equation or after a perturbation expansion to the second order in \( \alpha \) as done previously by Gilbert \[1, 2\].

The direct (small amplitude) Landau-Lifshitz frequency response is given by:

\[
\mu(\omega) = 1 + \frac{A + j\omega B}{(\omega_0^2 - \omega^2) + j\omega D}
\]

(3)

with:

\[
A = \gamma^2 M_s^2 (1 + \alpha^2) (1 + \frac{H_k}{M_s})
\]

(4)

and:

\[
B = \alpha \gamma M_s
\]

(5)

Moreover:

\[
C = \omega_0^2 = \gamma^2 H_k M_s (1 + \alpha^2) (1 + \frac{H_k}{M_s})
\]

(6)

and,

\[
D = \alpha \gamma M_s (1 + 2 \frac{H_k}{M_s})
\]

(7)

The reason behind this is the assumption that \( \alpha \) is small (smaller than 0.1) as confirmed experimentally.

The Gilbert and the L-L responses are compared in Fig. 1. As one expects, good agreement is visible between the two responses for small values of the damping parameter \( \alpha \). For larger values of \( \alpha \) (typically larger than 0.5) the responses start to differ and this difference would grow larger when non linear effects start to come into play.

In order to calculate the magnetisation as a function of time, we employ a fast time integration technique based on an accurate fourth order Runge-Kutta time domain integration scheme. The L-L equation is solved in the rotating frame (Larmor precession pulsation \( \omega = \gamma H_k \)) and the system is excited with a Dirac pulse in time. The FFT is then performed to get the frequency response. Since the amplitude of the exciting field \( h_y \) is small, the previous results might be directly compared with the linear response.

The studied \( Co_{100-x}Zr_x \), and \( Co_{100-x}ZrRe_x \) (3 < \( x \) < 14) amorphous thin films (of about 1 \( \mu \text{m} \) thickness) were deposited on 25 mm diameter glass substrate using conventional diode-sputtering equipment. The amorphous state has been verified by electron probe microanalysis and the thickness obtained by a profilometer. The materials present
an in-plane magnetisation. and their saturation magnetisation $M_s$, measured on a vibrating sample magnetometer, is higher than $10^6 A.m^{-1}$. The anisotropy field $H_k$ has been investigated with a B-H loopmeter and from ferromagnetic resonance linewidth.

A new broad-band method for the determination of complex magnetic permeability, described in [1], has been used.

The theoretical results are compared to experimental ones obtained on two kind of samples. The first one $Co_{95}Zr_{5}$ has a high uniaxial anisotropy field ($H_k = 2200 A.m^{-1}$) and a well defined anisotropy axis. The second one ($Co_{95}Zr_{5}$) has a smaller anisotropy field ($H_k = 400 A.m^{-1}$) and a distribution of the anisotropy axis. Further details of sample preparation are given in [1].

The first example of experimental spectra of the complex permeability is shown in figures 2 and -3. Good agreement between theoretical and experimental values can be observed. The linear and the non linear responses are compared to the experimental results. Real and imaginary parts are displayed separately in figure 2 for the L-L case and figure 3 for the non linear case.

The second example displayed in figures 4-5 concerns a $Co_{95}Zr_{5}$ thin amorphous film. The agreement between experiment and calculation is not so good in this case as already explained in [1] where the experimental data were compared to the Gilbert frequency response. The discrepancy might be attributed to the distribution of the anisotropy orientation. The real and imaginary parts of the full non linear response are displayed in figure 5.

In the set of figures we vary the value of $\alpha$ at will in order to estimate the interplay of linear and non linear effects. The results show that in spite of the relatively large variations in $\alpha$, the non linear response is close to the linear response in all cases. Nevertheless, the skewness of the imaginary part of the permeability follows better the non linear results.

In all cases, linear and non linear results for the real part of permeability obey the Stoner-Wohlfarth limit at small frequencies [1]. Non linear effects are visible but not strong enough to produce large departures from the linear results because of the small values of $\alpha$ considered.

III. CONCLUSION

This work considers the complex permeability at high frequency of thin ferromagnetic films, when the magnetisation is due to spin rotation. We have calculated, using linear and non-linear Landau-Lifshitz theory, the frequency dependence of the permeability of a uniaxial thin film with an in-plane anisotropy. We have shown the influence of non-linearity through the damping term $\alpha$ on the permeability spectra.

In the first batch of experimental results, good agreement with the model using Landau-Lifshitz theory is obtained whereas in the second batch of experimental measurements, we do not observe such a good agreement with theory.

Previously, other works considered eddy currents and the dispersion of uniaxial anisotropy as potential sources of discrepancy between theory and experiment. In this work, we investigated the effects of the non-linearity and confirm that it is not an issue in these materials in spite of an improvement in the skewness of the imaginary part of the permeability.

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[2] Van de Riet E. and Roozeboom F., J. App. Phys. 81 (1997) 350.
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**Figure Captions**

Fig. 1: Comparison between the Gilbert and the direct L-L frequency responses ($\alpha = 0.03$, $H_k = 2200 A.m^{-1}$ and $M_s = 1.15.10^6 A.m^{-1}$.)
Fig. 2: Real and imaginary part of the direct L-L frequency response and the measured spectrum of an amorphous \( \text{Co}_{95}\text{Zr}_{15} \) thin film when the exciting field is perpendicular to the easy axis. Thickness is 1 \( \mu \)m, \( H_k = 2200 \text{A.m}^{-1} \) and \( M_s = 1.15 \times 10^6 \text{A.m}^{-1} \).

Fig. 3: Real and imaginary part of the simulated non linear response and measured complex permeability frequency spectrum of an amorphous \( \text{Co}_{95}\text{Zr}_{15} \) thin film when the exciting field is perpendicular to the easy axis. Thickness is 1 \( \mu \)m, \( H_k = 2200 \text{A.m}^{-1} \) and \( M_s = 1.15 \times 10^6 \text{A.m}^{-1} \).

Fig. 4: Real and imaginary parts of the direct L-L linear response and the measured frequency spectrum of an amorphous \( \text{Co}_{95}\text{Zr}_{15} \) thin film when the exciting field is perpendicular to the easy axis. Thickness is 1 \( \mu \)m, \( H_k = 400 \text{A.m}^{-1} \) and \( M_s = 1.2 \times 10^6 \text{A.m}^{-1} \).

Fig. 5: Real and imaginary parts of the simulated non linear response and the measured complex permeability frequency spectrum of an amorphous \( \text{Co}_{95}\text{Zr}_{15} \) thin film when the exciting field is perpendicular to the easy axis. Thickness is 1 \( \mu \)m, \( H_k = 400 \text{A.m}^{-1} \) and \( M_s = 1.2 \times 10^6 \text{A.m}^{-1} \).
