Magnetization Transitions Obtained by Deconvolution of Measured Replay Pulses in Perpendicular Magnetic Recording.

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ABSTRACT.

Magnetization transitions in perpendicular magnetic recording have been calculated from measured replay pulses by a deconvolution algorithm using an analytical expression for the field of a probe head (PH). The transitions appear to be asymmetric whereby a pronounced magnetization peak occurs whose shape depends on the medium coercivity. For the experiments double layer media with double sided probe heads have been used. For the deconvolution only perpendicular head field and medium magnetization components are considered.

INTRODUCTION.

The reciprocity principle [1] can be applied to a perpendicular recording system, resulting in the well known convolution integral that relates replay flux to head field and medium magnetization. As stated in [2] the integral can also be considered as a correlation integral but since the perpendicular PH-field component is an even function, correlation and convolution are equivalent. We will therefore maintain the nomenclature convolution-deconvolution.

It has been quite common to estimate the replay flux by convolving an assumed magnetization transition and head field. In longitudinal recording an arctangent transition could very well explain the measured symmetric replay pulse shape [3]. In perpendicular recording, however, the observed replay pulses appear to be markedly asymmetric [4] also when a PH is used for writing and replay. The choice of a magnetization transition for a convolution is therefore not quite obvious. It is still desirable, of course, to estimate somehow the shape of the perpendicular transition. Transition models have been proposed which yield asymmetric transitions [5] and a maximum in the magnetization close to the transition [6,7,8]. This maximum is a consequence of demagnetization at large wavelengths which causes a decrease in the response at these wavelengths.

We followed a different (experimental) approach and chose to estimate the transition shape by deconvolving the measured replay pulse with the perpendicular PH-field. Of course certain assumptions have to be made about the magnetization components involved but this approach may lead to additional insight into the recording process. In longitudinal recording this method has proven to give realistic results when experimental noise enhancement caused by the deconvolution filter is sufficiently suppressed [9].

EXPERIMENTAL.

The measurements were carried out by means of an experimental floppy drive system especially designed for perpendicular magnetic recording. Double-layer CoCr-NiFe media on a flexible substrate (PET) were used (CoCr $M_s = 450$ kA/m; CoCr and NiFe thicknesses are both 400 nm) [10], and double sided probe heads with the main-pole auxiliary-pole structure as proposed by Iwasaki [4]. To realize the main pole, an amorphous zero-magnetostrictive CoZrNb alloy was RF-sputtered onto a glass substrate. The average relative main pole film permeability was about 3000, up to at least 10 MHz. The main pole film thickness was varied from 0.27 μm to 1.4 μm with a track width of 500 μm . For the auxiliary pole a ferrite bar with a 50 turn coil was employed. The relative head-to-medium velocity was 0.75 m/s.

The measured pulses were digitized and averaged over a number of revolutions to improve the signal to noise ratio.

The replay pulses we measured were clearly asymmetric, as shown in fig. 1. Replay pulse asymmetry may be caused by:

1. Nonlinear amplifier phase response.
2. Head asymmetry.
3. A contribution of longitudinal medium magnetization.
4. Perpendicular magnetization transition asymmetry.

The phase response of the replay amplifier was confirmed to be linear over a sufficiently large frequency range, which means that phase shift properties of the replay amplifier do not impose any replay pulse distortion.

From experiments with reversed write and replay directions it could be concluded that the head behaved symmetrically.

We will furthermore assume longitudinal medium magnetization to be negligible, which was found to be a good approximation due to the perpendicular anisotropy and low in-plane remanence of the CoCr layer [11]. Moreover, the head geometry favors the perpendicular magnetization component during recording as well as replay. When longitudinal magnetization is absent, it is possible to determine the perpendicular component through deconvolution [12].

Summarizing, it is concluded that the asymmetric replay pulse can be ascribed to

Figure 1. Example of a replay pulse from a main pole with thickness $T_m = 1.4 \mu\text{m}$.

an asymmetric perpendicular medium magnetization transition. Several authors have already demonstrated that an asymmetric magnetization transition will exist in the medium [5,6,7,8], and we have focussed our calculations on the explanation of the replay pulse shape by this asymmetry.

Between subsequent pulses a low constant value for the replay voltage is observed (fig. 1). With opposite replay direction the pulse showed a reversed shape as expected for any static magnetization pattern. This was not found for the output between the pulses. Therefore, we concluded that this voltage is not a result of a static magnetization pattern, and prior to the deconvolution we subtracted this background to avoid distortion of the calculated (static) magnetization pattern, (see fig. 3). No further explanation of this background has been found yet.

THEORY.

The reciprocity theorem applied to a perpendicular recording configuration yields the expression for the replay flux given in (1):

$$\phi(vr) = \mu_0 w \int_{-\infty}^{+\infty} M_y(x-vr) \int_a^{a+d} H_y(x,y) dy dx. \quad (1)$$

It is supposed that the perpendicular medium magnetization is constant over the CoCr thickness and it is furthermore assumed that both the CoCr magnetization and the head field are uniform over and confined to the track width. In (1) μ_0 is the permeability of free space, w the track width, a the spacing between head and CoCr layer and d the CoCr thickness. $H_y(x,y)$ is the head field at unity head coil current that would exist in the absence of the CoCr-layer [2]. For our further calculations we define a head field integrated over the medium thickness, given by (2), and from now on referred to as the integrated head field.

$$H'_y(x) = \frac{1}{d} \int_a^{a+d} H_y(x,y) dy \quad (2)$$

The integrated head field is calculated using Szczech's analytical expression [13] and for those cases where this expression was not valid ($T_m > (2.5(a+d))$) Steinback's solution [14] was employed. The y-field for the PH and Karlqvist's expression for the x-field of a ring head (RH) will be compared.

The convolution integral in (1) Fourier transformed and rewritten now gives the basic equation for the deconvolution algorithm:

$$\hat{M}_y(-k) = \frac{\hat{\phi}(k)}{\mu_0 w d \hat{H}'_y(k)}. \quad (3)$$

In (3), k is the wavenumber ($2\pi/\lambda$), λ being the recorded wavelength and $\hat{M}_y(-k)$ is the Fourier transform of $M_y(-x)$.

From now on, we are only interested in the shape of the mathematical functions involved, so any proportionality constants will be omitted. Scaling of any vertical

axis is therefore arbitrary. Because of the definition of the direction of medium motion and of the positive x -direction, which are the same, the most convenient way to compare the replay pulse shape and magnetization shape is to depict $e(+t)$ and $M_y(-x)$ together in one figure.

It is stressed that the outcome M_y of the deconvolution calculation is of course the magnetization shape during the presence of the head. This may result in a different magnetization shape compared to a relaxed magnetization state with the main pole at some remote distance from the medium.

DISCUSSION.

Choice of the head field used for deconvolution:

It is obvious that the head field chosen for deconvolution will have a very important influence on the calculated magnetization transition, so an appropriate choice of the head field used has to be made. Often, in a first approach, duality is assumed between H_x of a RH and H_y of a PH

Figure 2. Fourier transforms of the PH integrated head field (solid) and RH integrated head field (broken). The spatial integrated head fields are inserted.

A closer examination shows that this is certainly not true for the fields at large x -distances from the pole (response at large wavelengths). Therefore, the PH-fields [13,14] have to be used as discussed in [15]. The differences are illustrated in fig. 2 where the RH and PH integrated head fields are shown together with their Fourier transforms normalized for $k = 0$.

From the field properties in fig. 2, it can be expected that a RH-deconvolved magnetization spectrum will contain less high frequency content than a PH-deconvolved magnetization spectrum, which we will show later.

For the integration of the head field a proper choice of the head-to-medium spacing had to be made, which we estimated from harmonic response experiments at $0.1 \mu\text{m}$. It was verified that a change in the spacing did not influence the main features of the deconvolved transition to any large extent.

Noise suppression:

In practical circumstances the experimental replay pulse will contain noise which shows up as a noise level in the replay flux spectrum. The head field spectrum on the other hand reveals very pronounced pole nulls (fig. 2). With the application of [3], these pole nulls will cause unacceptable noise enhancement and thus unacceptable magnitudes of the corresponding frequency components in the calculated magnetization spectrum. These components can be suppressed by adding an artificial noise level to the head field spectrum. Addition of this noise level will only have a very strong influence on the magnetization spectrum components at or close to the pole-null frequencies. The noise level was then determined in such a way that a smooth magnetization spectrum resulted, even near the pole-null frequencies. A slightly different approach for this suboptimal way of inverse filtering is used in [9]. No additional filters and/or windows were used except a low-pass sinusoidal roll-off filter to get rid of very high frequency noise components. It was confirmed that no significant undulations were introduced by this filter.

RESULTS.

Thin T_m ($0.27 \mu\text{m}$). Fig. 3a shows the measured pulse shape (after correction for the background voltage) and fig. 3b shows the calculated magnetization pattern. The perpendicular coercivity of the medium is 18.3 kA/m .

The output voltage rises slowly with time. Next a steep decrease is followed by a small hump in the tail of the peak. The small T_m value causes the asymmetry of the pulse to be less pronounced than in fig. 1. The deconvolution for $T_m = 0.27 \mu\text{m}$ is relatively accurate because the pole-nulls do not markedly interfere

with the deconvolution. Fig. 3b shows the result of the deconvolution with the PH-field: an asymmetric transition with a peaked magnetization at the trailing side and a rather small magnetization peak at the leading side.

RH field. The results depend upon the field used for the deconvolution. This is illustrated in the broken curve in fig. 3b which shows the pattern obtained by using the integrated RH field. The transition shows a more gradual slope and a less pronounced peak. However, the asymmetry and peak are still present. Because the PH field is the most appropriate one in this configuration we will confine ourselves to results obtained with this field.

Figure 3. a) Measured replay pulse $T_m = 0.27 \mu\text{m}$. b) Transition obtained by PH-deconvolution (solid) and by RH-deconvolution (broken)

Thick T_m ($1.4 \mu\text{m}$). The pulse obtained with this T_m is shown in fig. 1. Deconvolution is less accurate in this case because the pole nulls occur at relatively large wavelengths and have to be taken into account properly to obtain reliable high frequency components of the magnetization spectrum. The transition is shown in fig. 4. ($H_c = 18.3 \text{ kA/m}$). The general features of $M_y(x)$ are comparable to the ones shown in fig. 3b

Figure 4. Transition by PH-deconvolution of corrected pulse in fig. 1.

Medium coercivity. The reasons for the peak in the magnetization are a low value for the demagnetizing field at the transition and demagnetization to $M = +$ or $-H_c$ far from the transition [6]. A magnetization exceeding H_c is possible during writing, but as soon as the transition is moved away from the head, the CoCr at the peak trailing side has to demagnetize. According to Suzuki et al. [6], the peak magnetization will be three times H_c . In figs. 3b and 4 the peak values are somewhat higher than $3 \cdot H_c$, possibly because the transition is wider than the ideal transition in [6] and because a small opposite peak appears at the leading side. But it should also be noted that the peak magnitude depends very much on the head field used for deconvolution. It can be expected that demagnetization will be stronger for lower H_c (same M_s) and that the magnetization peak in that case will be more pronounced. We also investigated the replay pulses for a higher coercivity (62.2 kA/m). The measured pulse and calculated transition are given in figs. 5a and b respectively. As expected, the pulse shape is different and surprisingly, the magnetization peak has almost disappeared. It can be concluded that the low frequency content for the magnetization increases for high H_c , as is also shown in [6]. Based upon [6] one might again expect a peak of about $3 \cdot H_c$ but this is not observed.

Pulse peaks. It is clear from the results, that the replay pulse peaks (fig. 1) are a genuine result of the transition shape (fig. 3b and 4). The replay pulse peaks

Figure 5. a) Measured replay pulse, $T_m = 1.4 \mu\text{m}$, $H_c = 62.2 \text{ kA/m}$.
b) Transition by PH-deconvolution of a).

are not a direct result of the observed head field peaks for constant y [13] because the peaks are absent in the integrated head field (fig. 2). This is supported by the pulse shape obtained for high H_c (fig. 5a), since the head field for this case and for low H_c are the same.

CONCLUSIONS.

The deconvolution calculations have revealed a markedly asymmetric perpendicular magnetization transition and a higher coercive CoCr layer was found to reduce the asymmetry and to increase the transition low frequency content. A remarkable difference was found for the spatial and Fourier transformed field properties of a RH and a PH, where the PH-model was the best approximation for the practical head used [15]. The replay pulse asymmetry is concluded to be a direct result of the magnetization transition and not of the field maxima in the non-integrated head field. The obtained asymmetric magnetization transitions show the features as predicted by transition models [6,7,8].

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