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COMPARISON BETWEEN LONGITUDINAL AND PERPENDICULAR MAGNETIC RECORDING AND REPRODUCE MECHANISMS

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INTRODUCTION

For quantitative analysis of magnetic recording and reproduction processes, we have developed a new computer simulation program based upon the finite element method (FEM) and the curling magnetization reversal model[1][2]. Using this program we already examined magnetic recording mechanisms and performances of both perpendicular and longitudinal magnetic recordings[3][4].

Using this FEM program, the simulation in the reproduction process as well as in the recording one can be performed taking the head–medium magnetic interaction into account. Conventionally the reciprocity theorem is widely used to calculate the reproduced output. In this paper, the reproduced waves calculated by the reciprocity are compared with those simulated by the FEM program. The reproduction mechanisms on the longitudinal and the perpendicular magnetic recordings are discussed.

RECIPROCITY THEOREM

Theory[5][6]

The reciprocity theorem in the reproduction process is brought from the reciprocity in the mutual inductance. Consider two coils, 1, 2, linked by a mutual inductance, L_m. A current, i_1, in coil 1 causes a magnetic flux ϕ_2 threading coil 2 given by

$$\phi_2 = L_m i_1 \tag{1}$$

This equation is consistent even if the subscripts, 1 and 2, are exchanged each other. Now take coil 1 to represent the coil of the reproduce–head and coil 2 to carry a minute coil to imagine at the position (x,y) in the recording medium. Then, the mutual inductance is given by

$$L_m = \phi_2(x,y)/i_1 \tag{2}.$$

Thus the distribution of $L_m(x,y)$ is in proportion to the magnetic flux distribution, ϕ_2, in the medium when the head is excited. If there is some flux source except the head coil, for instance magnetizations within the medium, the flux caused from that source have to be removed. The flux threading the minute coil, ϕ_2, is proportional to the normal component of the flux density $\mathbf{B}(x,y)$, and so

$$L_m(x,y) \propto \mathbf{B}(x,y)\cdot\mathbf{n}(x,y) \tag{3}$$

where $\mathbf{n}(x,y)$ is the unit vector normal to the minute coil, which is coincide with the unit vector of the magnetization, $\mathbf{M}(x,y)$.

On the other hand, the magnetization, $\mathbf{M}(x,y)$, in a minute element of the recording medium can be replaced with a solenoidal current of the minute coil, $i_m(x,y)$, is given by

$$i_m(x,y) = 4\pi M(x,y) \tag{4}$$

where $M(x,y)$ is the magnitude of the magnetization vector, $\mathbf{M}(x,y)$. The reciprocity principle exists between the minute coil and the head coil, and so the flux, ϕ_1, to thread the reproduce–head coil is given by

$$\phi_1 = L_m(x,y) i_m(x,y) \tag{5}.$$

Use of Eq.(3) and Eq.(4) in Eq.(5) gives

$$\begin{aligned}\phi_1 &\propto 4\pi\mathbf{B}(x,y)\cdot\mathbf{n}(x,y)M(x,y)\\ &\propto \mathbf{B}(x,y)\cdot\mathbf{M}(x,y)\end{aligned} \tag{6}.$$

Taking x–axis in the head velocity direction and y–axis in the medium thickness direction, and the total flux per unit track width in the reproduce–head coil is given by

$$\Phi = K\int_0^{\delta}\int_{-\infty}^{\infty}\mathbf{M}(x,y)\cdot\mathbf{B}(x,y)\,dx\,dy \tag{7}$$

Then an output voltage is given by differentiating Eq.(7). Here $\mathbf{B}(x,y)$ is called the reproduce–sensitivity function.

Since the proportion coefficient, K, depends on the heads and the media, we can not compare the outputs between different head–medium systems. However the reciprocity is useful for the analysis of the reproduce mechanism in detail because it is possible to calculate the contributions to the output from the x–component and the y–component of the magnetizations in the each layer of the medium.

Heads

This study was carried out for a metal-in-gap type ring head and a main-pole driven single pole type (SPT) head. Table 1 shows the relative permeability, μ, the saturation flux density, B_s, a gap length, g, a mail-pole thickness, T_m, and a head-medium separation, d, of each head.

Table 1 Head parameters

	Ring Head	SPT Head
μ	1100	4000
B_s (Gauss)	11000	20000
g / T_m (μm)	0.25	0.3
d (μm)	0.01	0.03

Media

For the media, a metal particle coated medium, a perpendicular oriented Ba-ferrite particulate medium and a Co-Cr/Ni-Fe double-layer medium were assumed. The saturation magnetization, M_s, the coercive field, H_c, the anisotropy field, H_k, the easy magnetization direction, E.A., the standard deviation of orientation distribution, σ_θ, the reduced standard deviation of anisotropy field distribution, σ_{hk}/H_k, the parameter on curling model, S, a thickness of recording layer, δ, the permeability of soft magnetic under layer, μ_{UL}, the saturation flux density of under layer, $B_{s,UL}$, and a thickness of under layer, δ_{UL}, are listed in table 2. These parameters were given as the result of fitting M-H loops calculated by the medium magnetization model to M-H loops measured by VSM. The ring head is used in combination with the metal particulate medium and the Ba-ferrite medium, and the SPT head is combined with the Co-Cr/Ni-Fe medium.

Table 2 Medium parameters

	Metal Particulate Medium	Ba-Ferrite Medium	Co-Cr / Ni-Fe Medium
M_s (emu/cc)	230	160	400
H_c (Oe)	1700	1700	1400
H_k (Oe)	4450	4450	5000
E.A. (deg)	0	90	90
σ_θ (deg)	25	25	8
σ_{hk} / H_k	0.29	0.09	0.07
S	1.68	1.68	1.96
δ (μm)	0.6	0.6	0.1
μ_{UL}	–	–	1000
$B_{s,UL}$ (Gauss)	–	–	7000
δ_{UL} (μm)	–	–	1.0

Recording Condition

The recorded magnetization distribution within the medium used both in the reciprocity calculation and FEM reproduction was prepared by the recording simulation in which the FEM program incorporating the medium magnetization model[1][2]. The recording current was set to a value at which the maximum reproduced voltage was obtained at each recording density. In the case of the SPT head and the Co-Cr/Ni-Fe medium combination, however, the recording current was fixed at an optimum for a low recording density because the optimum current hardly depends upon the recording density.

In the case of the metal particulate medium and the Co-Cr/Ni-Fe medium, we have obtained a good agreement between the simulated and the experimental results not only on the reproduced pulse forms but also on the recording density characteristics.

ISOLATED PULSEFORM

Sensitivity Function

Conventionally the head field distribution, $\mathbf{H}_h(x,y)$, calculated in the absence of the recording medium is used for the reproduce-sensitivity function, $\mathbf{B}(x,y)$, in Eq.(7). The field distribution, $\mathbf{H}(x,y)$, coincides with the flux density distribution, $\mathbf{B}(x,y)$ when the medium doesn't exist. But it's inadequate to use the head field distribution as the sensitivity function because the magnetized medium surely exists in the reproduce process. Therefore we have nominated the following four distributions as the reproduce-sensitivity function of the SPT head combined with the double layer medium, and its validity was discussed with respect to the obtained isolated waveforms.

[A] The head field distribution, $\mathbf{H}_h(x,y)$, calculated by the FEM incorporating the medium magnetization model under the condition of a very weak current not to magnetize the AC erased medium.

[B] The flux density distribution, $\mathbf{B}(x,y)$, obtained in the case of a proper current in the head coil, which saturate the AC erased medium under the main-pole of the SPT head.

[C] The effective field distribution, $\mathbf{H}_e(x,y)$, obtained after subtracting the magnetization distribution, $\mathbf{M}(x,y)$, from the flux density distribution, $\mathbf{B}(x,y)$, on [B].

[D] The field distribution calculated by the Karlqvist equations considering the magnetic charges on the main-pole tip and its image magnetic charge in the soft magnetic under layer.

Figure 1 shows the distributions of the reproduce-sensitivity functions at the surface of the Co-Cr layer. The distribution of [B] is sharper than that of [A] because the magnetic interaction between the head and the medium on [B] is stronger than that on [A]. The reason for the broad distribution of [C] is that the effective field distribution, $\mathbf{H}_e(x,y)$ is broadened by the influence of the demagnetizing field, $\mathbf{H}_d$, diminishing the head field, $\mathbf{H}_h$.

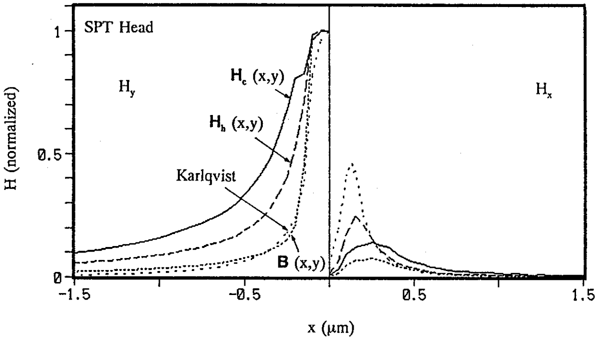

Figure 1 Reproduce-sensitivity functions

Pulseform Comparison

Figure 2 shows the reproduced voltage waveforms for isolated transitions simulated by the FEM program and calculated by the reciprocity theorem using the four types of the reproduce-sensitivity function as described above. The waveform obtained by the reciprocity in which the effective field distribution, $\mathbf{H}_e(x,y)$, is used for the sensitivity function is much broader than that for the FEM simulation. The waveforms for the reciprocity with the sensitivity function of flux density distribution, $\mathbf{B}(x,y)$, and the Karlqvist distribution are sharper than that for the FEM. When the head field distribution, $\mathbf{H}_h(x,y)$, is introduced as the sensitivity function, we get a good agreement between the waveforms obtained by the reciprocity and by the FEM. These results suggests that the head-medium magnetic interaction is not so strong in the reproduce process because the magnetizations in the reproduction are much smaller than the saturation magnetization.

HIGH DENSITY WAVEFORM

Proportion Coefficient

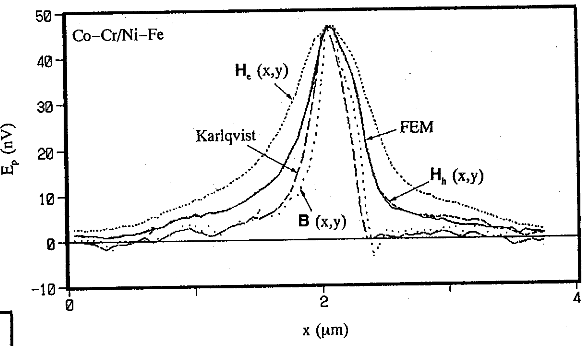

Figure 2 Isolated pulses obtained for the Co-Cr/Ni-Fe double-layer medium and the SPT head combination

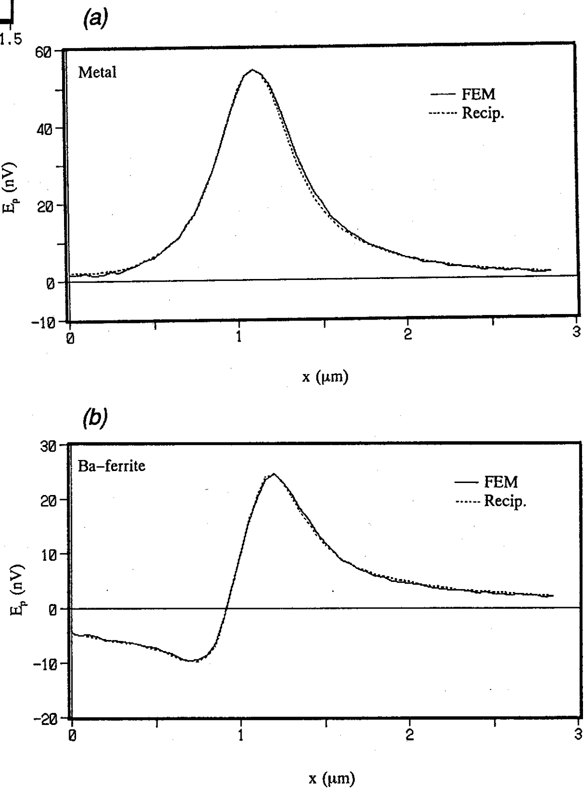

Figure 3 Isolated pulses for (a) the metal particulate medium and (b) the Ba-ferrite medium

Figure 3 shows the isolated pulseforms obtained by the FEM and the reciprocity in the case that (a) the metal particulate and (b) the Ba-ferrite particulate media are assumed. The pulseforms for the FEM and the reciprocity coincide each other very well. Here the head field distribution, $\mathbf{H}_h(x,y)$, of [A] was used for the sensitivity function.

We have set the proportion coefficient, K, in Eq.(7) as shown in table 3 so that the pulse maximum calculated by the reciprocity might coincide with that simulated by the FEM. We can see that the coefficient, K, changes extremely as the head changes. But K doesn't depend upon both a recording density and a recording current. Therefore the coefficient, K, has been fixed at the value in Table 3 on the following calculations.

Table 3 Proportion coefficients

	Ring Head		SPT Head
	Metal Particulate Medium	Ba-Ferrite Medium	Co-Cr / Fe-Ni Medium
K	0.0552	0.0532	0.1076

Waveform Comparison

Figure 4 shows the waveform of the reproduced voltage at a density of 102 kFRPI for (a) the metal particulate medium, (b) the Ba-ferrite medium and (c) Co-Cr/Ni-Fe double layer medium, where the solid and broken lines are the results for the FEM simulation and the reciprocity calculation respectively. The output waves coincide roughly each other in the case of the metal particulate medium, but there is a little difference on the waves for the Co-Cr/Ni-Fe medium. In the case of the Ba-ferrite medium, the output for the reciprocity is much smaller than that for the FEM. The possible reasons to this difference are;

[E] The magnetization distribution in the reproduction is different from that in the remanent state because the existence of the highly permeable reproduce-head decreases the demagnetizing field in the medium.

[F] The reproduce-sensitivity function changes according to the magnetization distribution within the medium changes because the permeability changes locally in the medium.

[G] The sensitivity function changes because the head is saturated partially by the leakage flux from the recorded medium even in the reproduce process.

Magnetization Distribution

First of all, let's consider about [E]. Figure 5 shows the perpendicular component distributions of the magnetization at the surface layer of the medium in the remanent state (solid lines) and in the reproduce process (broken lines) obtained by the FEM simulation for the Ba-ferrite medium. When the ring head comes in close to the medium in the reproduction, the demagnetizing field within the medium decreases because the surface magnetic charges are partially canceled by the image charges in the ring head. Resultantly the magnetizations in the medium increase. Figure 6 shows the output waves calculated by the FEM (solid line) and by the reciproc-

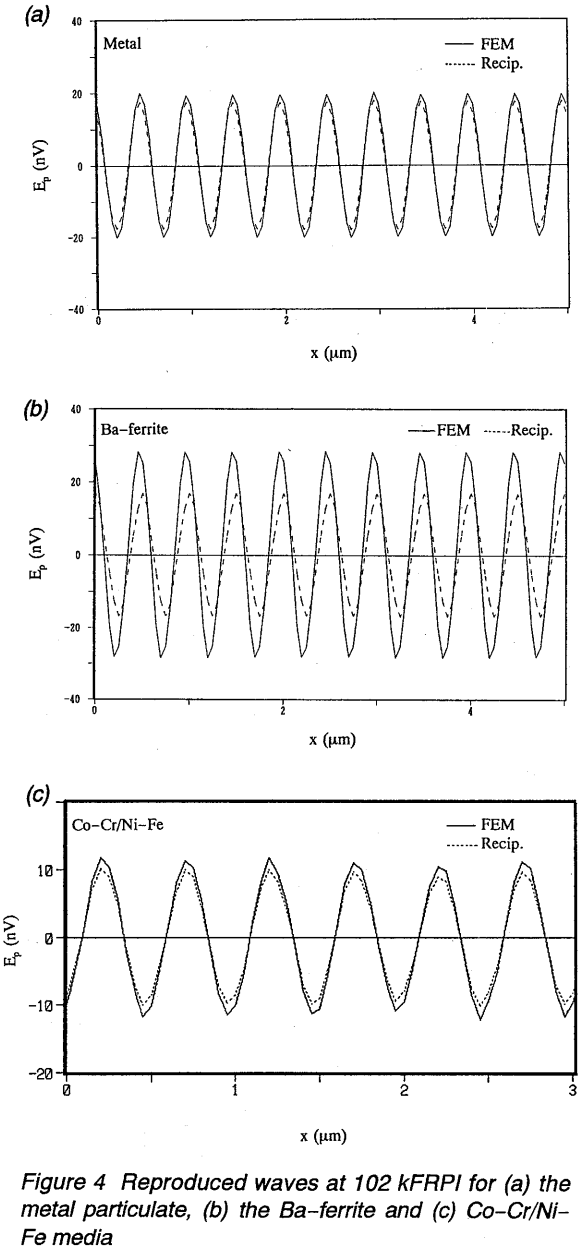

Figure 4 Reproduced waves at 102 kFRPI for (a) the metal particulate, (b) the Ba-ferrite and (c) Co-Cr/Ni-Fe media

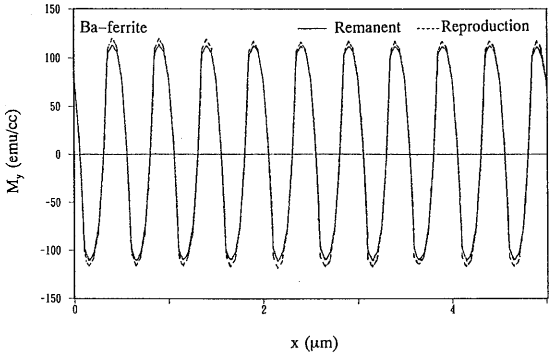

Figure 5 Perpendicular magnetization distributions in the remanent and the reproduction states

ity in which the remanent magnetizations (broken lines) and the magnetizations in the reproduction (dotted lines) were used. The output for the magnetizations in the reproduction is larger than that calculated for the remanent magnetizations because of the increase of the magnetization. However its output increment is very small.

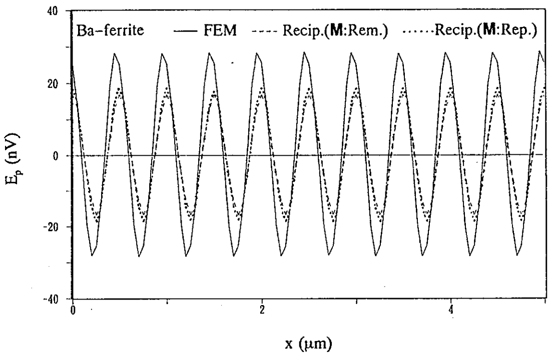

Figure 6 Reproduced waves for the FEM and for the reciprocity calculations

Therefore the reason for the difference on the output waves is that the reproduce-sensitivity function changes as the magnetization pattern within the medium changes. Since the output for the reciprocity is smaller than that for the FEM, it is clear that the sensitivity function has to be sharper than that assumed here in the case of a high recording density. This suggests that the head-medium magnetic interaction is stronger at a high density than that for an isolated transition. Therefore we conclude that the use of the sharper distribution than the distribution of [A] is substantially proper for the sensitivity function at a high density.

Medium Permeability

The permeability, μ, is the proportion of the flux density, B, to the field, H, and so

$$\mu(x,y)=B(x,y)/H(x,y)$$
$$=1+4\pi M(x,y)/H(x,y) \qquad (8)$$

It is clear that the permeability within the medium is not unit and changes locally when the medium is magnetized. This suggests that the reproduce-sensitivity function also changes when the medium is magnetized.

Head Saturation

The magnetic flux leaked from the recorded medium surface is unexpectedly large in the reproduce process. In the case of the Co-Cr/Ni-Fe double layer medium, it have been obtained by the FEM simulation that the flux density nearby the medium surface is from several hundreds to over one thousand (Gauss). Therefore it seems that the head may be saturated in the reproduce process and the reproduce-sensitivity function changes.

SUMMARY

The reproduced voltage wave calculated by the reciprocity theorem was compared with that obtained by the FEM simulation. A good agreement was obtained on the isolated pulse, but the difference has appeared at a high recording density. This is because the reproduce-sensitivity function assumed as the head field distribution is broader than precise one at a high density.

Since the sensitivity function changes as the magnetization distribution within the medium changes, the FEM simulation program incorporating the medium magnetization model is necessary to analyze the reproduction process as well as the recording one. But in the case of the longitudinal magnetic recording, the calculation based upon the reciprocity gives the good agreement with the results of FEM calculation because of the weak head-medium magnetic interaction.

We suppose that the change of the sensitivity function of the reproduce-head is caused by the change of the permeability distribution in the medium and the head saturation in the reproduce process. In order to clear the reasons why the sensitivity function changes, the further investigation is necessary.

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