Simplified Expression of Shielded MR Head Response for Double-Layer Perpendicular Medium

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***Abstract*--- An approximated simple expression of MR head response was given for perpendicular double-layer media. The equation was derived by modifying Fan's equation so as to be of a nonintegral form. The validity was confirmed by comparisons with exact solutions of the Fan' equation, which resulted in errors of less than 10 % for practical applications of recent MR heads. Using the expression, the reciprocity theorem revealed that the measured transition length of perpendicular recording was extremely small, less than 10 nm.**

***Index terms*--- perpendicular magnetic recording, MR head, double-layer medium, reciprocity theorem**

I. INTRODUCTION

In perpendicular magnetic recording using a single-pole writing-head, a narrow PW_{50} of 130 nm for an AMR head having a shield spacing of 210 nm was measured, even for a relatively large magnetic spacing of 50 nm [1]. Theoretical calculations using the reciprocity theorem in association with a head sensitivity function based on Fan's equation [2] indicated that the calculated response approximately agreed with the measured PW_{50}. However, the calculation was rather complicated because Fan's equation consists of an infinite series including infinite integrations. A simpler expression may be more convenient.

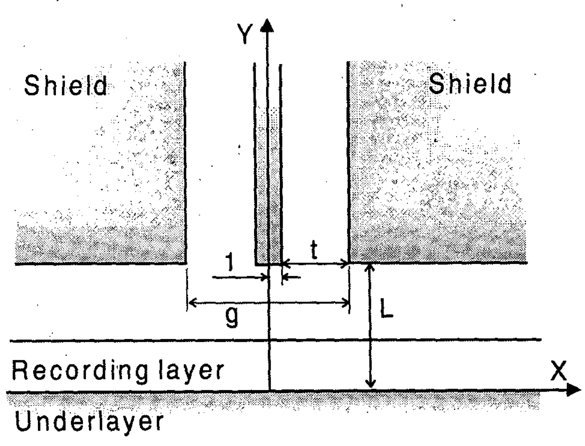

Fig.1 Coordinate system for the calculation. t, g and L are the distance between the MR stripe and the shield, the shield-to-shield spacing and the head-to-underlayer distance. They are normalized to half the thickness of the MR stripe. The underlayer of the medium was assumed to have infinite thickness and permeability.

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In addition, information on the transition length of perpendicular magnetic recording is required to in order to evaluate its future potential. Few comparisons between the theoretical solution and experimental results have been carried out. It is still not clear what determines the PW_{50} of a readback waveform for a given head/disk system including the transition length.

In this paper, a simple, approximated expression of the head sensitivity function is first provided in order to easily calculate the isolated transition response. Then, using the function, an detailed comparison between the calculation and the experimental waveform is presented.

II. APPROXIMATED SENSITIVITY EXPRESSION

The head sensitivity function, *Hy*, derived from the original Fan's equations is listed below as (1) through (4) [1]. The coordinate system and parameters were as shown in Fig. 1. Here, the parameter, L, is magnetic separation between the ABS and the top of the underlayer, and t is the gap between the shield and the MR sensor. The shield-to-shield spacing is represented by g. Cn' in (2) is given as the solutions of (4), which is a set of algebraic equations.

$$Hy(x,y)=\int_0^\infty \frac{Lt(k,t)}{k}\cdot\cos(kx)\cdot\frac{\cosh(ky)}{\sinh(kL)}dk \qquad (1).$$

$$Lt(k,t)=\frac{4}{t\pi}\cdot\sin\left(\frac{k(t+2)}{2}\right)\cdot\sin\left(\frac{kt}{2}\right)+\frac{2}{\pi}\cdot k^2\cdot\sum_n Cn'\cdot\Psi n(t,k) \qquad (2).$$

$$\Psi n(t,k)=\int_1^{t+1}\sin\frac{n\pi\cdot(k-1)}{t}\cdot\cos(kx)dx \qquad (3).$$

$$-Cm'\frac{m\pi}{2}=\frac{4}{\pi t}\int_0^\infty \coth(kL)\frac{\sin(k(t+2)/2)\cdot\sin(kt/2)}{k}\Psi m(t,k)dk+\frac{2}{\pi}\sum Cn'\int_0^\infty k\cdot\coth(kL)\cdot\Psi n(t,k)\cdot\Psi m(t,k)dk \qquad (4).$$

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The most inconvenient problem of (1) to (4) is the infinite integral operations. When everything except the first term of $Lt(k,t)$ in (2) was neglected, the calculation to solve the coefficient Cn' and the function Ψn is no longer required, which results in a great simplification. Then, using the relationship of $0.5/\sinh(x) = \exp(-x)+\exp(-3x)+\exp(-5x)+...$ and changing the products of the trigonometric functions into a summation series, the infinite integral of (1) can be obtained analytically. Thus, (1) can finally be written as the following simple equations (5) and (6)

$$Hy(x,y) = \frac{1}{2t\pi}\sum_{i=1}^{\infty}\left\{f(x,(2i-1)L-y)+f(x,(2i-1)L+y)\right\} \quad (5)$$

$$f(X,Y) = \ln\left(\frac{(t+1+X)^2+Y^2}{(1+X)^2+Y^2}\right)+\ln\left(\frac{(t+1-X)^2+Y^2}{(1-X)^2+Y^2}\right) \quad (6)$$

The above equations mean that the sensitivity function is expressed as the sum of a series of head sensitivity functions $f(X,Y)$ caused by the mirror effect of the soft-magnetic underlayer and the head surface, which is schematically indicated in Fig. 2. Equation (6) gives the individual head sensitivity function. The individual function, $f(X,Y)$, consists of two ring heads separated by $t+2$, which is the same as in Potter's modeling of MR heads [3]. The summation in (5) is rapidly convergent. Fig. 3 shows the contribution of each successive term in the case of L=100 nm, t=90 nm, y= 25 nm, in which each term's contribution to the peak at x=0 is 81%, 11%, 4%, 2%, 1%. Therefore, a summation of the first five terms is sufficient in most cases

Some calculated results from (5) and (6) are plotted in Fig. 4 and compared with the exact solution of Fan's equations. The magnetic spacing and recording layer thickness were both 50nm. The field is calculated along the center of recording layer, i.e. at y=25nm. Although the approximation gives slightly broader distributions, they were satisfactory for the cases in which the shield-to-shield spacing was less than twice the sum of the magnetic spacing and recording layer thickness. Another calculation for the case where the magnetic spacing, recording layer thickness and y were 25nm, 25nm and 12.5nm respectively brought a similar result.

A head sensitivity function corresponding measurements described later is shown in Fig. 5, here the magnetic spacing and recording layer thickness were both 50 nm and the shield spacing was 210nm. The distribution width at the 50 % level was expanded by around 10 % compared to the exact solution in this case. In the figure, two cases for effective shield spacings, which were smaller than the mechanical spacing by 5% and 10% respectively, are also plotted. A reduction of the shield spacing by around 5% to 10% resulted in a better agreement.

III. COMPARISON WITH EXPERIMENTAL RESULTS

By substituting the approximated head sensitivity function into the following reciprocity theorem, the readback waveform were calculated. The magnetization distribution in the medium was assumed to be uniform along the y-direction, and to be represented by an arctangent magnetization transition. When the parameter of the arctangent function, a, is sufficiently small, (7) gives the narrowest response.

$$Ep(\tau) = \int_{-\infty}^{\infty}\int_{0}^{\delta}\tan^{-1}((\tau-x)/a)\cdot Hy(x,y)\,dy\,dx \quad (7)$$

Here, δ is the recording layer thickness, and τ is the relative displacement between the head and the medium.

Fig. 6 shows the waveforms calculated by (7), in which the approximated expressions of (5) and (6) were used for the head sensitivity function, $Hy(x,y)$. The calculation was made for transition parameters, a, of 1, 10 and 30nm. The exact solution of the Fan's equation also used for an infinitely small transition length, and is plotted with crosshair symbols. A

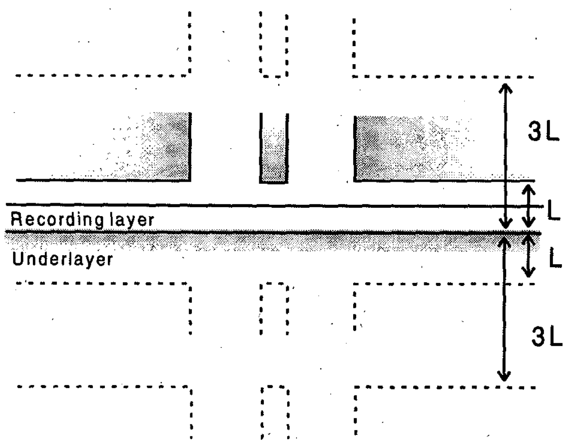

Fig. 2 Schematic explanation of the derived approximated head sensitivity function of the MR head for the double layer perpendicular medium.

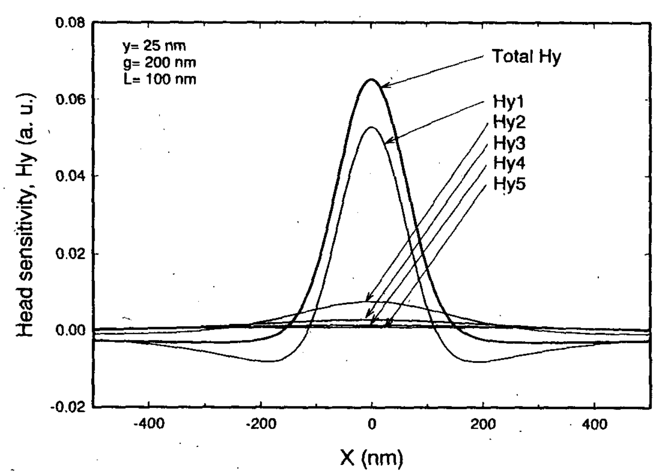

Fig. 3 Contributions of each term for the series expression of the approximated Hy. L= 100nm, t= 9nm, y= 25nm.

measured waveform is also plotted for comparison as filled circles. For a real medium, permeability of the soft-magnetic underlayer isn't infinite, which modifies the head sensitivity function in strict meaning. We ignored this influence, because sufficiently high permeability the underlayer was expected in the experiment.

The approximation for the 1nm transition length provided almost the same response as the calculation using the exact solution. The approximated expression thus had a satisfactory accuracy for practical situations. The calculation in which the shield spacing was assumed to be 90 % of the mechanical shield spacing, as described above, also showed a very slight difference. Transition lengths of 10nm or less gave the best agreement with the measured result, because, as can be seen in the figure 6, there was clear difference for the transition length of 30nm. The readback response is mostly determined by the

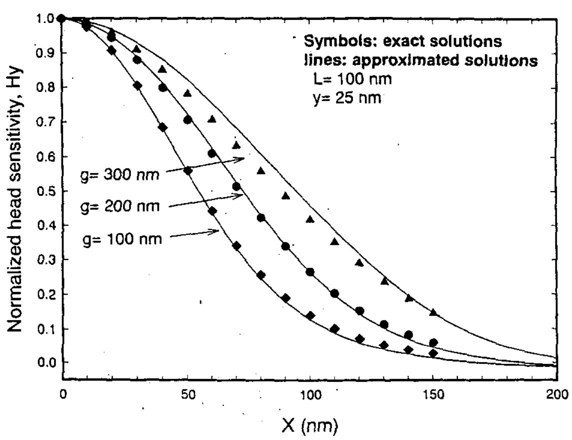

Fig. 4 Comparisons between the approximated field distributions and the exact solution Magnetic spacing, recording layer thickness and y are 50nm, 50nm and 25nm respectively. Only positive values of x are shown because of the symmetry.

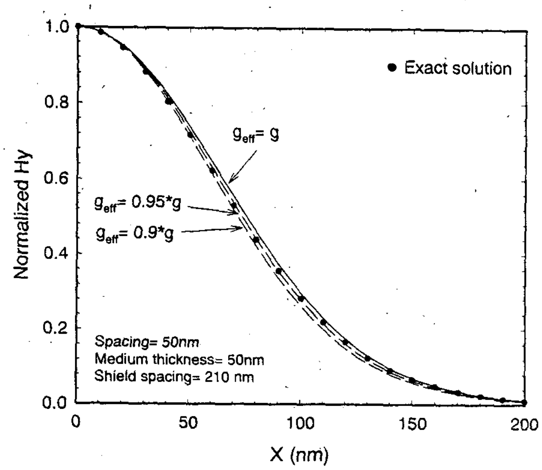

Fig. 5 Improvement of accuracy by introduction of an effective shield spacing. The effective shield spacing was set to 90% and 95% of the mechanical shield spacing. A half plane is shown because of the symmetry.

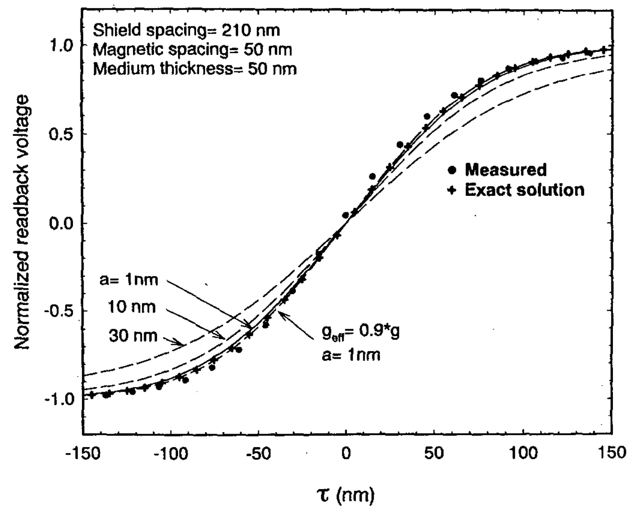

Fig. 6 Comparison between calculated waveforms for various transition lengths and an experimental result. The measured data were obtained with an MR head whose shield spacing was 210nm, and the estimated magnetic spacing was 50nm. The thickness of the disk used in the experiment was 50nm.

read head resolution. A sufficient estimation will therefore be obtained only by taking into account the reading characteristics.

IV. Conclusion

A simple expression for the readback response of shielded MR heads was given for perpendicularly magnetized double layer disks by modifying Fan's equation. By comparisons with exact solutions of the equations, we determined that the approximation is valid for cases where the shield-to-shield spacing of an MR head is smaller than twice the sum of the magnetic spacing and recording layer thickness. Using the sensitivity function of an MR head, readback responses were also calculated and compared with a measured result. The best agreement was obtained when the transition length was zero. It was thus concluded that negligibly small transition length was realized in perpendicular magnetic recording using a double-layer medium with single-pole head writing.

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