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The read spacing losses in perpendicular magnetic recording have been investigated experimentally for various combinations of heads and media. The spacing loss coefficient K, which is the slope of the line resulting when the spacing loss is plotted against d/λ, has been measured for sinusoidal magnetization. The results show that for a single layer medium, K is almost the same as that in longitudinal recording, and that for a double layer medium, the K value is large at long wavelengths and becomes small with decreasing wavelength. For ring heads in particular, a striking wavelength dependence of K is observed. Such a wavelength dependence results from the change in the distribution and the magnitude of the head sensitivity function with the spacing. Nevertheless, in digital recording the deterioration of recording density characteristics with increasing spacing is small, even at low densities, because of the contribution of harmonics in output signals.

I. Introduction

In perpendicular recording, judicious choice of various parameters, such as the thickness and magnetic properties of the main pole in single-pole heads and the thickness, saturation magnetization and coercivity of the Co-Cr layer in the perpendicular magnetic recording media, is effective for inducing a strong magnetic interaction between the main pole and the medium, thereby achieving a high signal-to-noise ratio and superior recording density characteristics [1]-[3]. Previously the authors measured the spacing losses for perpendicular recording media with a spacer material affixed to the medium surface, and reported that the spacing loss differs from that already reported for longitudinal recording, and that the loss for

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single-pole heads is smaller than that for ring heads [4],[5]. The increase in the mechanical spacing acts to weaken the magnetic coupling between the main pole and medium, and thus affects the spacing loss as well.

A number of theoretical studies on read spacing losses have been conducted [6]-[9]; in this paper, the results of detailed measurements of the spacing loss, for combinations of single-pole and ring heads with Co-Cr single-layer media and Co-Cr/Ni-Fe double-layer media, are described. In the measurements, aside from mechanically varying the spacing using spacers, losses at smaller spacings and shorter wavelengths were investigated by performing fast Fourier transform (FFT) analyses of waveforms, and estimating losses from the attentuation of higher harmonics.

II. Methods for Measurement of Read Spacing Losses

A. Direct Measurements Using Spacers

The authors in previous studies measured the spacing losses for digital signals with a spacer inserted between the head and medium during recording and reproducing [4]. But as the effects of the recording process are contained in the results, and because high harmonic components are included in the digital signals, it is not possible to accurately appraise the spacing loss on the basis of these results alone. For this reason, the effect of the spacing during reading was measured for sinusoidal magnetizations.

Table 1. Geometric dimensions of heads

Head	Type	T_m or g, (μm)	W, (mm)
SPT-1	Single-Pole	1	2
SPT-2	Single-Pole	0.4	2
SPT-3	Single-Pole	0.7	2
SPT-4	Single-Pole	0.9	2
RT-1	Ring	0.6	2

Table 2. Magnetic properties of media

Medium	Layer	$\delta_{Co\text{-}Cr}$, (μm)	$H_{C\perp}$, (Oe)	M_S, (emu/cc)	δ_{BL}, (μm)
DL-1	Double	0.26	750	710	0.5
DL-2	Double	0.34	500	400	0.5
DL-3	Double	0.26	570	710	0.5
SL-1	Single	0.25	750	450	—
SL-2	Single	0.21	570	450	—

Single-pole heads, the specifications of which appear in Table 1, were used to conduct saturation recording, while in contact with the medium, of all 1's signals in NRZI code. During reading, a titanium foil spacer (of thickness d ranging from 0.9 to 37.3 microns) was inserted between head and medium, and signals were reproduced using the heads of Table 1. In this way, the attenuation of reproduced signals for different spacings was measured for a number of recording wavelengths. The single-layer and double-layer media whose specifications appear in Table 2 were employed.

Figs. 1 and 2 present the components of the reproduced signal as a parameter of wavelength responses of the fundamental spacer thickness, as recorded with a single-pole head and reproduced with (A) a ring head and (B) a single-pole head, for a single-layer Co-Cr medium and a double-layer Co-Cr/Ni-Fe medium, respectively.

(1) The effect of the read spacing is generally greater for double-layer media with a soft magnetic layer.

(2) For ring heads as opposed to single-pole heads in particular, in the long wavelength region the attenuation due to the spacing is greater.

From these results, we conclude the following:

(3) There are flat portions at intermediate wavelengths in the characteristics for the ring-head/double-layer medium combination, which extend to longer wavelengths as the spacing is increased.

(4) The slope of the wavelength response at longer wavelengths for the single-pole head/double-layer medium combination is somewhat gentler than 6 dB/octave, and is considerably more gentle for single-layer media.

These basic tendencies of waveform response have been explained theoretically [3],[6],[10].

In particular, the difference in the performance of ring and single-pole heads in combination with double-layer media is

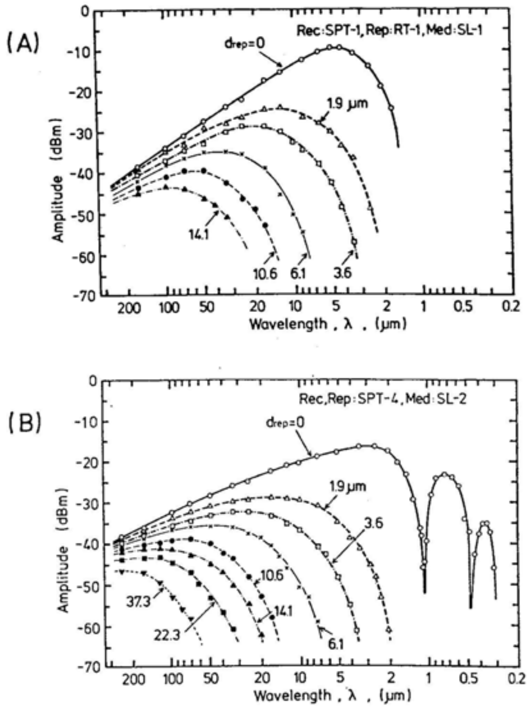

Fig. 1. Wavelength response for sinusoidal magnetization in single-layer media for (A) ring head reading and (B) single-pole head reading.

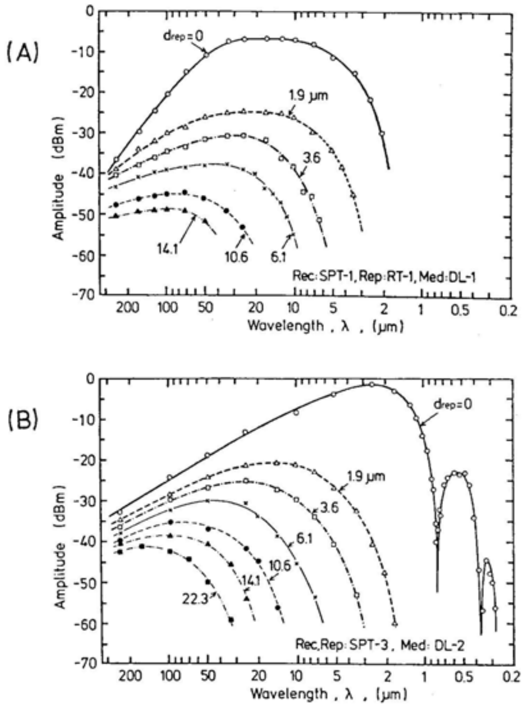

Fig. 2. Wavelength response for sinusoidal magnetization in double-layer media for (A) ring head reading and (B) single-pole head reading.

caused by the fact that, for the ring head, the head cores couple magnetically with the medium over a wide area of the core's front surface, as opposed to the restraints imposed by the main pole thickness for single-pole heads.

Further, the difference in behavior of single-layer and double-layer media is due to the magnetic interaction with the head of the soft magnetic layer of double-layer media, which is especially strong compared with single-layer media.

B. Measurements by the FFT Method

In measurements employing spacers, there are limits in preparing thin films with the mechanical strength required to withstand testing, and it is difficult to perform direct measurements for small spacings below 1 or 2 microns. In addition, a deteriorated signal-to-noise ratio makes measurement of spacing losses at shorter wavelengths difficult as well. In order to measure read spacing losses for recording wavelengths under 10 microns and small spacings suited to practical applications, FFT was used in Fourier analyses of reproduced waveforms, and spacing losses were determined from the attenuation of the higher harmonics.

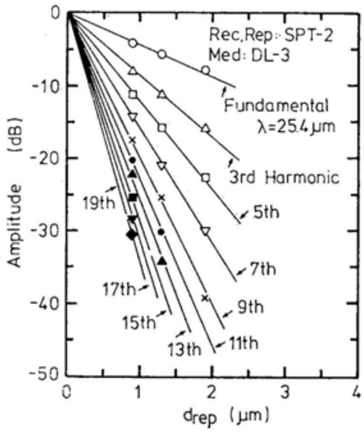

Fig. 3. Spacing losses of fundamental component and harmonics of output signals.

Fig. 3 plots the attenuations, with increasing head/medium spacing during reproduction of the components of a 2 kFRPI reproduced waveform from the fundamental to the 19th harmonic, for a single-pole head and double-layer medium, and with spacer thicknesses varied between 0.9, 1.3 and 1.9 microns. From the figure, the spacing loss may be approximated by the following formula, for the spacings under 2 microns employed:

$$\text{spacing loss} = K(d/\lambda)\ \text{dB} \qquad (1)$$

Here K, which we shall call the spacing loss coefficient, is a function of the wavelength λ, as is clear from Fig. 3.

Thus by measuring the changes in harmonics in the frequency spectrum of a reproduced waveform by FFT, the spacing loss coefficient for short wavelengths may at once be determined.

Further, in conducting analyses by this method using a computer, prior to FFT processing a number of reproduced waveforms are averaged, to raise the measurement accuracy.

III. Read Spacing Losses for Various Head/Medium Combinations

Fig. 4 shows the decreases in reproduced voltage with increasing spacing, obtained by plotting the results of Fig. 2 for various recording wavelengths.

For double-layer media, and especially in combination with ring heads, the spacing loss shows a pronounced dependence on the wavelength. For a given value of d/λ, the longer the wavelength λ, the greater the drop in the reproduced voltage. For single-layer media, on the other hand, whether used with ring or single-pole heads, the read spacing loss coefficient is nearly equal to 54.6, the value derived from the theory of read processes in longitudinal recording.

Fig. 5 shows the recording wavelength dependences of the spacing loss coefficient K, taken as the slopes of the lines in Figs. 1 through 3 for the spacings of under 2 microns, that is, for d/λ ~ 0. Data in the figure at wavelengths of 10 microns or longer are obtained by direct measurements using spacers, those at shorter wavelengths by FFT waveform analyses. The two sets of results show continuity, suggesting the reasonableness of the FFT method of measurement.

From these results we note the following tendencies:

(1) For single-layer media, at recording wavelengths below 50 microns the loss coefficient is equal to about 54.6, and is somewhat larger at longer wavelengths.

(2) For double-layer media, when a ring head is used the dependence of the spacing loss coefficient on the recording wavelength is conspicuous, and at longer wavelengths the coefficient is extremely large, but as the recording wavelengths become shorter it becomes smaller.

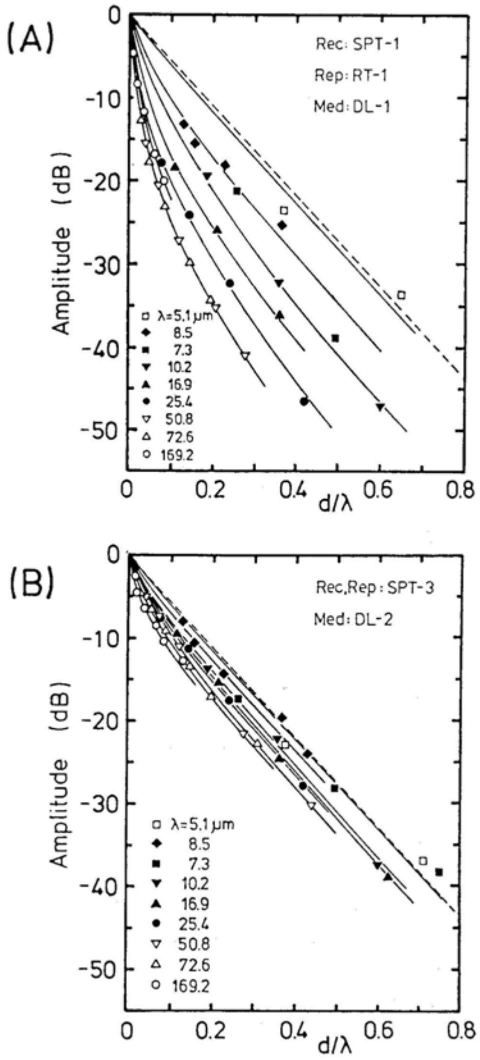

Fig. 4. Spacing loss versus d/λ for (A) a ring head and (B) a single-pole head.

According to the reciprocity theorem, the magnetic flux linked with the head coil may be found by taking the volume integral of the product of the magnetic field distribution of reproducing head driven by unit

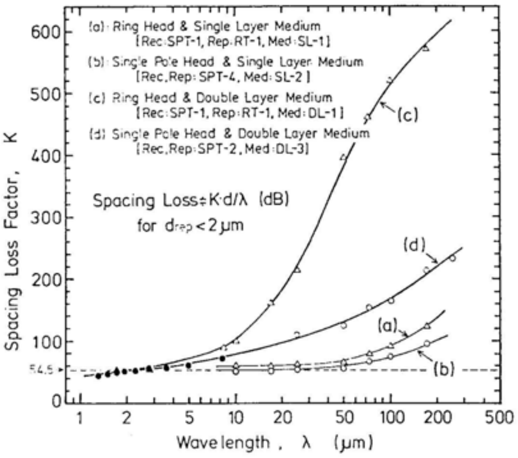

Fig. 5. Spacing loss coefficient K versus recording wavelength.

magnetomotive force with the magnetization distribution in the medium. Thus the reproducing head field distribution becomes equal to the reproducing sensitivity function, and for a sinusoidal magnetization distribution, the reproduced voltage amplitude is determined by the peak amplitude and distribution of the reading sensitivity function for a given spacing.

In single-layer media, similar to the case of conventional longitudinal recording, the small permeability of the magnetic layer results in a comparatively weak magnetic coupling between the head and medium, so that the medium exerts little influence on the head. Thus even when the spacing is increased, and even when the recording wavelength is varied, the loss coefficient is still around 54.6, the value derived from the field distribution attenuation in the absence of a medium. But for double-layer media the strength of the magnetic interaction between the head core and the soft magnetic layer of the medium changes with the spacing. For single-pole heads, the smaller the spacing, the stronger the magnetic coupling between the main pole of the head and the soft magnetic layer of the medium, and the perpendicular component of the field is concentrated in the area between the main pole and the soft magnetic layer. Hence the reproducing sensitivity function is essentially determined within the region delimited by the main pole thickness, and has an extremely steep distribution; moreover, its amplitude attenuation at greater distances from the main pole tip is small [5].

But as the spacing is increased the sensitivity function is distributed over a broader region, and the amplitude attentuation at distances from the pole tip is also larger. Accordingly, for long-wavelength recording in which the integral of the reproducing sensitivity function in the medium magnetization layer determines the reproduced voltage, changes in the reproducing sensitivity function due to larger spacings will result in considerable attenuation of the reproduced voltage.

For ring heads, the region of interaction between the head core and medium is much broader than for single-pole heads, and the reproducing sensitivity function extends to distances far removed from the ring head gap. For this reason the longer the wavelength, at which the range of integration is wider, the greater the influence of change in the sensitivity function due to spacing.

But for both ring and single-pole heads, as the wavelength becomes shorter, the integration range which relates to the read flux is narrowed roughly in proportion to the wavelength, so that the decrease in reproduced voltage caused by the change of magnitude of the reproducing sensitivity function is distributed due to the lessening of spacing. As a result, the loss coefficient gradually approaches Wallace's value of 54.6. Actual measurements indicate that at even shorter wavelengths the value tends to become even smaller; more detailed investigation is necessary.

IV. Dependences of the Read Spacing Loss on the Head and Medium Constants

The behavior of the read spacing loss described in the above has been reported based on the reciprocity theorem, using the head field distribution calculated with only the soft magnetic layer of the medium and the head core considered [6]-[9]. As this method is used in calculations for a ring head, with a core of infinite length, or infinite permeability, the results differ considerably from the behavior of actual measurements, such as in Fig. 4.

Also, as the authors have already pointed out [2], the Co-Cr perpendicular anisotropy layers of perpendicular media have large saturation magnetizations, so that the magnetic interaction between this layer and the head cannot be ignored. This is also evident [3] from finite-element method analyses, which show that the magnetic flux distribution for a single-pole head/double-layer medium combination differs from that for a soft magnetic layer alone, without the Co-Cr layer. These facts signify the need for investigations of the effects of the head magnetic interaction with not only the soft magnetic layer, but with the Co-Cr layer of double-layer media as well.

Fig. 6 shows the measured relations of the read spacing loss to (A) the main pole thickness, (B) the Co-Cr layer thickness, and (C) the magnitude of the Co-Cr layer saturation magnetization. The attenuation of the fundamental component amplitude due to the spacing was measured at 2 kFRPI (or a recording wavelength of 25.4 microns), at which density the effect of the spacing tends to be pronounced. As the main pole is made thicker, and the Co-Cr layer made thinner, and the larger the saturation magnetization of the latter, the larger the spacing loss.

As the main pole thickness increases and the Co-Cr layer is made thinner, the distance between the main pole and the soft magnetic layer is reduced; and as the Co-Cr saturation magnetization is raised, the demagnetization at the tip of the main pole is lessened, all of which act to strengthen the main pole-medium magnetic coupling. When the head-medium magnetic interaction is strong, the perpendicular magnetic field tends to be concentrated between the two, so that the reproducing sensitivity is enhanced considerably, and at the same

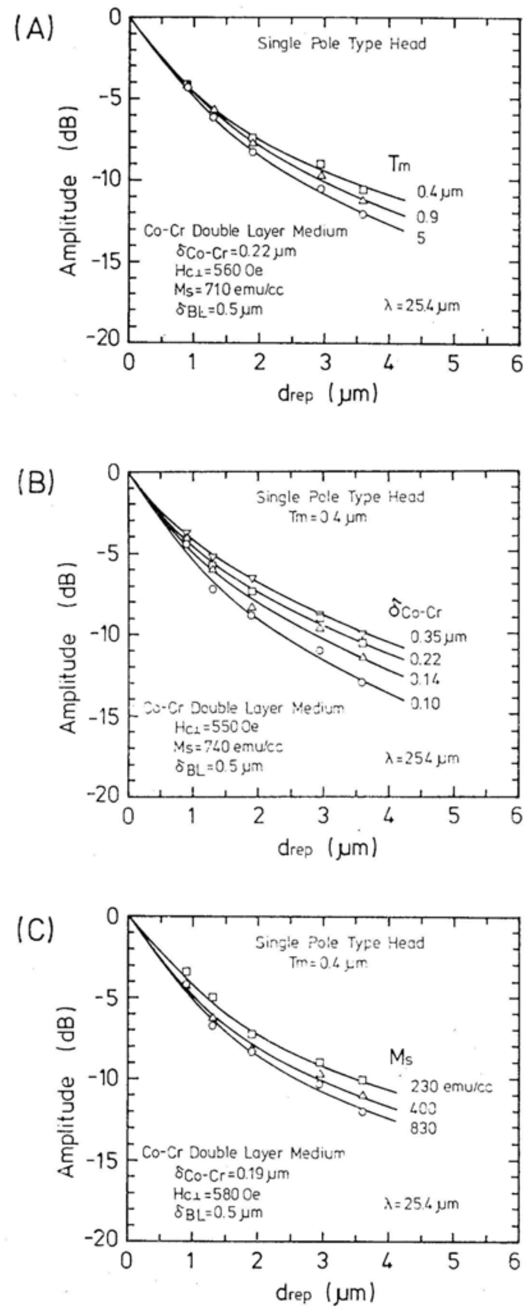

Fig. 6. Effects of main pole thickness (A), thickness (B) and saturation magnetization (C) of Co-Cr layer on the spacing loss.

time the sensitivity distribution becomes sharper, for better resolution. In other words, if the spacing is increased, the magnetic field distribution function changes to the same extent, and the reproduced voltage is decreased.

V. The Effect of the Read Spacing in Digital Recording

Here we investigate, using computer simulations, the influence of the recording wavelength dependence of the read spacing loss coefficient on digital recording, for a double-layer medium/single-pole head combination.

Let us suppose that, during reproduction with the head in contact with the medium, a rectangular pulse (of pulse width 0.4 µs) was reproduced for the isolated magnetization transition. After transforming this into a frequency domain, we attenuate each of the frequency components according to the spacing loss coefficients actually measured (Fig. 5(d)), then perform an inverse Fourier transform of the resulting spectrum, to obtain the reproduced waveform for a nonzero spacing. The changes in the pulse height and width at half-maximum with the spacing are shown in Fig. 7. For comparison, the results obtained assuming that the loss coefficient is independent of the wavelength (and constant at 54.6) are also shown as dashed lines. In digital recording, the contribution of the higher harmonic components is considerable, and spacing losses are clearly reflected in the results for short-wavelength

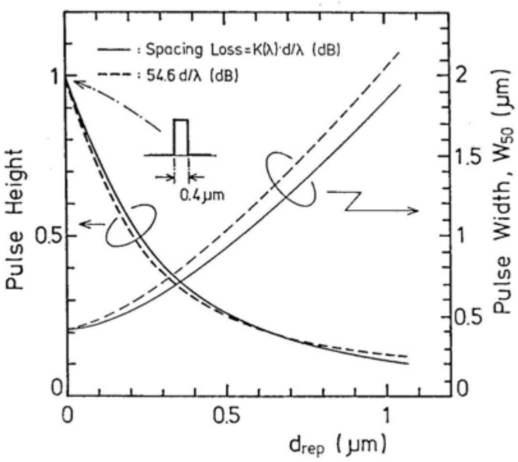

Fig. 7. Pulse height and pulse width versus spacing.

sinusoidal magnetization; thus inclusion of the actual wavelength dependence of the loss coefficient results in less attenuation of the pulse height with increased spacing, and also less pulse broadening. Hence it is inferred that deterioration in the high-density recording characteristics due to the spacing will be smaller than that for an independent loss coefficient on the wavelength. From the above, in digital perpendicular magnetic recording, such wavelength dependence of the spacing loss coefficient for sinusoidal magnetization for small spacings can be said to be advantageous.

VI. Conclusion

In the present work, the read spacing losses for the various combinations of single- and double-layer media with ring and single-pole magnetic heads were investigated.

Perpendicular magnetic recording employing double-layer media and single-pole heads can make effective use of the magnetic interaction between the main pole and the medium, to achieve superior recording/reproducing characteristics. To take advantage of this, it is desirable that the head-medium spacing be as small as possible; and even within the range of spacings actually possible, excellent performances may be realized.

It was also shown that in theoretical explanations of the characteristics including spacing loss in perpendicular magnetic recording, the magnetic interaction between the main pole and the Co-Cr layer cannot be neglected. Therefore, a method for analyzing the magnetic field must be introduced which accounts for the effect of the Co-Cr layer on the head magnetization, for example [11].

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References

[1] Ouchi and Iwasaki, Rep. Tech. Grp. Magn. Rec. IECE Japan, MR83-7, 1983.
[2] Iwasaki, Nakamura, and Muraoka, Dig. 2nd Ann. Conf. Magn. Japan, 22aA-5, 1978.
[3] Nakamura, Takeda, and Iwasaki, Rep. Tech. Grp. Magn. Rec. IECE Japan, MR84-10, 1984.
[4] S. Iwasaki, D.E. Speliotis, and S. Yamamoto, IEEE Trans. Magn., Vol.MAG-19, No.5, p.1126,

1983.
[5] Iwasaki, Nakamura, and Yamamoto, Nat. Conf. Rec. Semicon. Devices & Mat., IECE Japan, 57, 1983.
[6] Satake, Honda, and Hokkyo, J. Magn. Soc. Jpn., Vol.8, No.2, p.81, 1984.
[7] B. Baker, 3M Conf., HP-06, 1984.
[8] B. Baker, J. Appl. Phys., Vol.55, No.6, p.2217, 1984.
[9] O. Lopez, IEEE Trans. Magn., Vol.MAG-19, No.5, p.1614, 1984.
[10] T. Fujiwara and K. Yamamori, IEEE Trans. Magn., Vol.MAG-18, No.6, p.1244, 1982.
[11] S. Tanabe and S. Iwasaki, 3M Conf., FB-08, 1984.