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Thermally Induced Pulses in Magnetoresistive Heads

Abstract: The thermal response of a magnetoresistive head is analyzed for frictional heating between the head surface and dust particles or other asperities on the recording medium surface during relative motion of head and medium. A theoretical model is presented showing that pulses are induced in the output of a magnetoresistive head as a result of this frictional heating. The model predicts the dependence of these thermal noise spikes on the thermal properties of the substrate and cover chip for the magnetoresistive head, the dimensions of the magnetoresistive stripe, the head-medium relative velocity, and the rate of frictional heat generation. Experimental verification of the theoretical model is obtained by scanning a focused laser beam across a head.

Introduction

Hunt has described a novel thin film transducer, using the magnetoresistive effect [1] for magnetic applications. Because the resistance of a magnetoresistive (MR) film is temperature dependent, the thermal response of an MR head to frictional heat sources results in noise in its output. Thermal noise spikes have been observed by Gorter and Potgiesser [2] in the output of an MR head used in a cassette recorder.

In this paper, a theoretical model is given to predict the thermal response of an MR head to frictional heat sources. To test the predictions of the model, a laser beam was focused and scanned across an MR head (Fig. 1) to simulate a frictional heat source and the head output was measured.

Model for thermal noise spikes

The configuration studied is a thin (<500Å) vertical stripe of MR material (such as an 83:17 NiFe evaporated permalloy film) on a substrate with a cover chip "glued" on as shown in Fig. 1. A constant current is passed through the MR stripe in the direction parallel to the magnetic easy axis and the voltage across the stripe is monitored.

• *Frictional heat source*

Consider a frictional heat source such as a particle of dust or an asperity on the recording medium being dragged across the head surface by the moving medium. The temperatures of the substrate, magnetoresistive stripe, and cover chip rise because of this heat source. Since the MR stripe is thin it responds only to the temperature of the material surrounding it—acting like an ideal thermometer. By assuming that the "glue" holding the cover chip is negligibly thin, the temperature distribution in the substrate and cover chip can be approximated by the temperature distribution in a solid block of material having the same thermal properties as the substrate and cover chip material (referred to later as the host material).

The temperature rise at a point in the magnetoresistive stripe can then be approximated as being equal to the calculated temperature rise at the equivalent position in the solid block. This approximate temperature rise can be used with the temperature coefficient of resistivity for the magnetoresistive material to compute a resistance rise for the stripe and the resulting voltage output.

It has been shown [3] that for a *point* heat source of magnitude q moving at velocity v in the x direction across a plane surface (x-y plane, Fig. 1) of material with thermal conductivity k and thermal diffusivity α(where $\alpha = k/C$, the value C being the heat capacity per unit volume), the temperature in the material at a point (x, y, z) at time t is given by

$$T(\xi, y, z) = q \{\exp [-v(\xi + r)/2\alpha]\}/2\pi kr, \qquad (1)$$

where

$$r = (\xi^2 + y^2 + z^2)^{\frac{1}{2}} \qquad (2)$$

and

$$\xi = x - vt. \qquad (3)$$

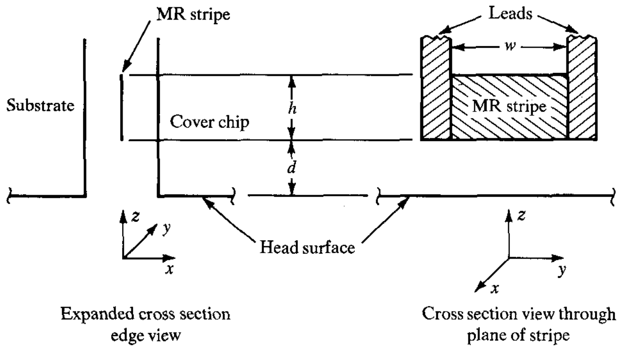

Figure 1 Configuration of a magnetoresistive head.

By neglecting the very small nonuniformity in current density in the MR stripe resulting from the spatial dependence of the resistivity rise, the resistance rise of the stripe can be taken as proportional to the *average* temperature rise of the stripe. The temperature distribution of the MR stripe in the y-z plane at $x = 0$, given by Eq. (1), can be averaged over the dimensions of the stripe (throat height h and track width w):

$$\overline{T} = \frac{q \exp v^2 t/2\alpha.}{2\pi k w h} \int_{-\frac{w}{2}}^{+\frac{w}{2}} dy \int_{d}^{d+h} dz \times \frac{\exp\{-v\,[(vt)^2 + y^2 + z^2]^{\frac{1}{2}}/2\alpha\}}{[(vt)^2 + y^2 + z^2]^{\frac{1}{2}}}, \qquad (4)$$

where d is the distance from the outside edge of the substrate to the outer edge of the MR stripe (Fig. 1). This integral must be computed numerically for each set of variables.

The case of maximum magnetic reading resolution, $d = 0$, presents a difficulty because of the singularity in the integrand at $t = y = z = 0$. This difficulty can be avoided by transforming from the (y, z) coordinates to cylindrical coordinates $[\rho = (y^2 + z^2)^{\frac{1}{2}},\ \phi = \tan^{-1}(y/z)]$ and then transforming again to the coordinates $\beta = [(vt)^2 + \rho^2]^{\frac{1}{2}}$, ϕ. The integration over β can then be done exactly. Using C for the specific heat of the material *per unit volume*, the result is

$$\overline{T}(t) = \frac{q \exp[+(v^2/2\alpha)(t - |t|)]}{vCwh} \times \Big\{1 - \frac{2}{\pi}\int_0^{\tan^{-1} w/2h} d\phi \times \exp\Big(-\frac{v}{2\alpha}\{[(vt)^2 + (h \sec\phi)^2]^{\frac{1}{2}} - (v|t|)\}\Big) - \frac{2}{\pi}\int_{\tan^{-1} w/2h}^{\pi/2} d\phi \times \exp\Big(-\frac{v}{2\alpha}\{[(vt)^2 + \Big(\frac{w}{2}\operatorname{cosec}\phi\Big)^2]^{\frac{1}{2}} - (v|t|)\}\Big)\Big\}. \qquad (5)$$

Because the singularity in the integrand has been integrated out, the remaining integral may be computed numerically.

Because of the requirement for numerical calculations to compute $\overline{T}$ from Eq. (5), approximate expressions for $\overline{T}$ under the conditions of interest are useful to obtain the dependence of the thermal response on the parameters. Approximate forms for Eq. (5) can be derived for two limited ranges of parameters. The first pertains to high speed magnetic reading such as in a tape drive or disk file. The other is valid for low speeds, as in the operation of the magnetic head described by Bajorek, et al. [4].

For high speed reading, if a ceramic substrate is used, a reasonable value for α would be 0.01 cm^2/s. Typical head-medium velocities are greater than or of the order of 250 cm/s (100 ips), yielding a size for the region of thermal influence (α/v) less than or equal to 0.4 μm. This region is small compared with typical values for $h(\approx 25\ \mu m)$ or $w(\approx 100\ \mu m)$. If attention is further limited to times such that the distance (vt) between the heat source and the stripe is small compared to h and w, then

$$\overline{T}(t) \cong q \exp[v^2(t - |t|)/2\alpha]vCwh. \qquad (6)$$

In this expression, the magnitude of the noise spike is inversely proportional to the heat capacity per unit volume and independent of the thermal conductivity of the material. Physical aspects of this dependence can be understood by considering that thermal conductivity affects only the size of the region of thermal influence, whereas the heat capacity per unit volume governs the size of the temperature rise in that region. At the time of maximum temperature, the heat source is located directly over the stripe and hence the stripe is a plane through the whole region of thermal influence. Thus, its average temperature is independent of the size of the region of thermal influence (and hence of the thermal conductivity) but is inversely proportional to the heat capacity per unit volume. This dependence on heat capacity offers little ability to lower the magnitude by changing the substrate material for the following reason. The heat capacity per atom at room temperature is nearly independent of the material; thus the heat capacity per unit volume will depend only on the packing density of the atoms, which varies little for different materials.

The time dependence given by Eq. (6) shows an exponential temperature rise for $t < 0$ with a time constant α/v^2 as long as h and w are large compared to α/v. When this condition is not satisfied, the rise will be even faster. A maximum in temperature is reached at $t = 0$ (i.e., no thermal lag). Equation (6) shows no decay for $t > 0$ because the decay is contained in the last two terms of Eq. (5), which were neglected for times $t \ll h/v$ and w/v. Thus, the decay must take place on a time scale

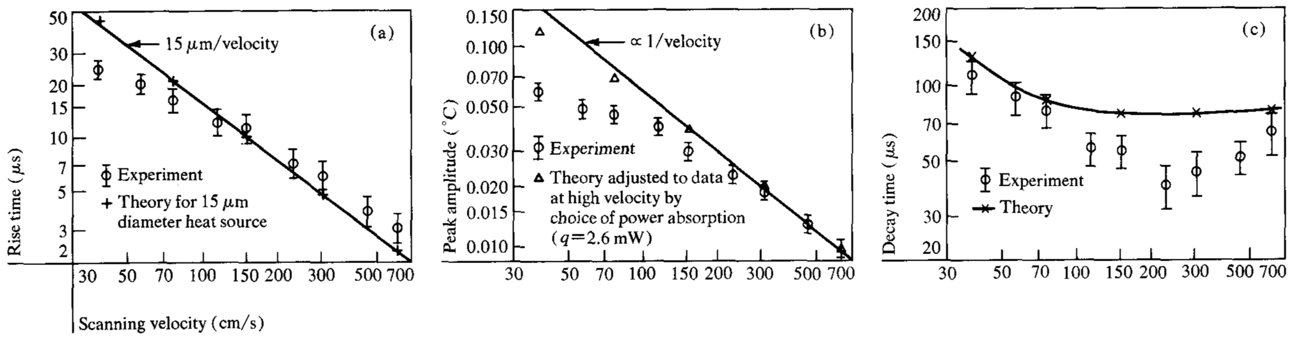

Figure 2 Laser scan data. MR stripe output due to laser scanning as a function of scanning velocity. (a) Risetime, (b) peak amplitude, and (c) decay time (peak to half-peak).

corresponding to the time h/v required for the heat source to move the distance of the throat height from the stripe (assuming $h < w$).

The second approximate form for Eq. (5) is valid for low speeds and is useful in analyzing the magnetic head described by Bajorek et al. [4]. In the range $\alpha/v \gtrsim 25$ μm, the spatial variation of the temperature over the dimensions of the stripe ($h = 20$ μm, $w = 75$ μm, $d = 40$ μm) is small and nearly independent of k, C, and v as can be seen from Eq. (1). Hence, the average temperature over the stripe can be approximated by

$$T \approx q \exp\left[-v(\xi + r_0)/2\alpha\right]/2\pi k r_0, \qquad (7)$$

where

$$r_0 = (\xi^2 + y_0^2 + z_0^2)^{\frac{1}{2}} \qquad (8)$$

and y_0 and z_0 are constants on the order of $w/2$ and $(d + h/2)$, respectively. From this expression we see that the amplitude is independent of C and v but inversely proportional to k. This behavior is just the opposite to that observed for the high-speed limit. Thus, for this case the amplitude of the thermal response can be lowered by choosing a host material of high thermal conductivity. The time dependence from Eq. (7) shows a temperature rise that is a combination of an exponential term with a 10 to 100 percent risetime of 2.3 α/v^2 and a $1/r_0$ term with a 10 to 100 percent risetime of 10 $(y_0^2 + z_0^2)^{\frac{1}{2}}/v$. Because these times are comparable, the actual risetime will be less than either. The maximum is shifted from $t = 0$ (i.e., there is a thermal lag) and the decay time 100 to 10 percent is 10 $(y_0^2 + z_0^2)^{\frac{1}{2}}/v$.

In all cases, the size of the thermal response is proportional to q, which depends upon the frictional force F between the particle and substrate and the velocity:

$$q = Fv. \qquad (9)$$

From the adhesion theory of friction, we expect the frictional force F to be given by [5]:

$$F = \langle\tau\rangle A_r \geq \langle\tau\rangle L/p, \qquad (10)$$

where $\langle\tau\rangle$ is the average shear stress over the real area of contact A_r for a load L and a penetration hardness p for the head surface or particle, whichever is lower. From Eq. (10) we see that the frictional force should be approximately independent of velocity as long as a change in velocity is not accompanied by a change in load. Thus, we expect the heat input q to be approximately proportional to velocity. For the limit of high-speed heads, Eq. (6) shows that this implies an approximate independence of amplitude from velocity as long as the particle load is not altered by velocity. In the low speed limit an approximately linear dependence of amplitude on velocity is shown by Eq. (7) for a constant load.

The analysis so far has been for a point heat source, but in the actual situation the heat source has a finite size. The effect of finite-sized particles can be approximated by averaging Eq. (5) over an interval of ξ in length equal to the particle length l and centered on the center of the particle. As expected, the results show that as long as the time required for the particle to pass over the stripe, l/v, is much larger than the characteristic risetime α/v^2, the temperature risetime is given by l/v. When l/v is smaller than or comparable to α/v^2, the risetime is larger than l/v.

Experimental observations

A laser beam was focused onto and scanned across the surface of an MR head to check the analytical model for frictional heating. In Fig. 2(a) the risetime of the stripe output is plotted as a function of scanning velocity. The data fit the theoretical predictions except at low velocity, if a beam diameter of 15 μm is assumed. Although the beam diameter was not measured, the assumed value of 15 μm is reasonable. The discrepancy at lower velocities is probably due to a thermal barrier between the MR stripe and the substrate, caused by a thin interleaving ceramic layer and the resulting interfaces. The amplitude as a function of scanning velocity is shown in Fig. 2(b), along with the model predictions. Again, the data fit model predictions except at low velocities. Finally, the time of decay from peak amplitude to half-peak amplitude is plotted along with the model predictions in Fig. 2(c) as a function of scanning velocity. Decay times shorter than predicted values would also be expected from the neglected thermal barrier.

Two MR heads of the type described by Bajorek, et al. [4], one with sapphire substrate and cover chip and the other with silicon, were scanned with a laser at 37.5 cm/s (15 ips). The surfaces of both of these heads were covered with a 1 000 Å film of evaporated aluminum to insure that the laser beam produced a heat source at the surface which was the same for both silicon and sapphire (because sapphire is transparent). The ratio of the peak amplitudes for these two heads is

$$\frac{\Delta T_{\text{sapphire}}}{\Delta T_{\text{silicon}}} = 2.6 \pm 0.3,$$

whereas the prediction of the model is 2.4. The average risetimes (for 10 to 100 percent of peak amplitude), 180 μs and 350 μs, were measured for sapphire and silicon, respectively, compared to predicted values of 190 μs and 400 μs. Average decay times (for 100 to 33 percent of peak amplitude) of 160 μs and 70 μs were measured for sapphire and silicon, respectively, compared to 240 μs and 200 μs from the model. This discrepancy between the observed and predicted decay times is probably due to the low thermal conductivity of the glue used to attach the cover chip. Care was taken to scan in a direction such that the laser traversed the substrate first and then traversed the cover chip, so that the decay time would be expected to be shortened if the glue line were thick enough. This effect would be greater for silicon than for sapphire, as observed. In general, the laser scanning experiments confirm the predictions of the model as long as the thermal barriers between the MR stripe and the substrate and cover chip are negligible, as assumed.

Summary

It has been shown that the thermal response of magnetoresistive heads results in noise spikes in their output. From the model for frictional heating, it can be shown that the signal-to-noise ratio decreases linearly with the track width and throat height as long as the region of thermal influence (α/v) and the heat source size are much smaller than the track width and throat height. Further decreases in track width and throat height result in additional decreases in signal-to-noise ratio at a rate slower than linear. Potter [6], in discussing the advantages of MR heads over inductive heads for high density magnetic recording, has concluded that a track width of 6 μm is possible if thermal noise spikes are neglected. It is clear that thermal noise spikes are an important problem to be overcome if this potential use for MR heads is to be achieved.

Acknowledgments

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