Keeped Media Recording: super-resolution for magnetic recording

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Abstract--- Keeped media are made up of two layers: a conventional hard longitudinal film plus a soft magnetic film or "keeper" layer. To recover the written data, a small DC bias current is applied to the inductive readback head. The nonlinear behavior of the soft film in the presence of the bias field provides the mechanism for super-resolution. This paper reviews the history and principles of keeped recording. The structure and fabrication of keeped media are described. Measurements are presented which show the improved resolution and amplitude and which quantify the noise, nonlinearity, and sidereading/sidewriting behavior. Several other "keeped" configurations including perpendicular options are described. Work is ongoing to optimize the performance of keeped media with MR heads. There is also evidence that the keeper stabilizes the stored data and will extend the superparamagnetic limit on areal recording density

I. INTRODUCTION

The hard disk-drive industry is currently maintaining a remarkable 60% per annum growth rate in information storage density. However, there is not a lot that is fundamentally new in magnetic recording technology. Today, just as fifty years ago, commercial products use a "ring" head writing on a "longitudinal" recording medium. The two most recent innovations in the Hard Disk Drive industry, magneto-resistive (MR) heads and the Partial-Response Maximum-Likelihood (PRML) read/write channels were both invented nearly 30 years ago. Neither of these innovations alters the basic writing process or the storage mode. "Perpendicular" recording does represent a quite different recording technique. In two-layer perpendicular media a soft magnetic film is placed below the hard storage layer. This film, which is relatively thick, serves to reinforce and 'focus' the fields during write and also improves the head-efficiency during read. Perpendicular recording has been the focus of intense research, particularly in Japan. So far, however, perpendicular recording has not become commercially successful.

Keeped recording is a very novel approach which changes the storage and readback modes considerably. As in perpendicular recording, the recording medium includes a soft film. In keeped media, however, the soft film plays a very different role. In the typical keeped media configuration, an additional thin layer of magnetically soft film (a "keeper") is deposited on top of an otherwise conventional longitudinal medium, Figure

1. In order to recover the recorded information, a small DC bias current must be applied to the inductive readback head. Because of the bias, the thin soft film saturates locally in the proximity of the head gap. The nonlinear behavior of the soft film provides the mechanism for superresolution in the readback process. The reproduced pulses are found not only to be narrower but also to have increased amplitude.

The concept of keeped recording arose in 1984 [1,2] as one of a series of intriguing innovations arising from the work of Gooch at Ampex Corporation. Thin layers of soft saturable film were being proposed in a variety of applications ranging from electronic track-following to low wear-rate rotary scanners [3-6]. In the following years, however, work on keeped recording paused as activities on hard disk drives at Ampex ceased. Interest was revived at various times from 1990 to 1996 with a number of companies pursuing the technique as an alternative to MR head technology [7,8]. In academia, the University of Minnesota has maintained an ongoing activity in both the theory and the implementation of keeped recording [9,10]. Recent work by Wilson et al. at Stanford University has focused on overcoming some of the nonlinear distortions inherent in the technique [11].

The work of Sawazaki bears some relationship to keeped recording. Sawazaki proposed that soft magnetic material be included into the tape medium but that AC-bias (rather than a DC-bias) be used in a parametric readback mode [12,13]. Also Mallory has proposed using a thick underlying soft film spaced away from the hard film as a means of reducing sidereading effects [14].

In an interesting analog of keeped recording, Murakami et al. [15] describe a magneto-optical system giving superresolution in which the anisotropy of a soft overlayer is switched by heat from an incident laser spot.

Keeped recording has not yet appeared in any commercial products. However, interest in the technology has recently been rekindled by the recognition that this storage mode is intrinsically very stable. At very high areal densities approaching the

Figure 1. Keepered recording system diagram. Read connection provides dc bias current in the head coil to produce virtual gap in keeper layer

superparamagnetic limit, magnetization decay can occur just from thermal excitation. The keeper dramatically reduces the internal demagnetizing fields and thus reduces the rate of decay. The keeper also reduces the extent of sidewriting effects and is thus very compatible with recording at low bit-aspect ratio and very high track-density. Current activity has thus focused on the compatibility of keepered media with magnetoresistive heads and on the possibility that keepered recording may ultimately allow higher areal densities to be achieved.

II. PRINCIPLES OF KEEPERED RECORDING

A. Fundamental Concepts

The most common configuration for keepered recording consists of a ring head and a medium made up of a magnetically hard recording layer and a soft "keeper" layer. Figure 1 represents schematically a typical system. The recording and keeper layers are separated by a thin break layer to prevent exchange coupling between the two layers. The soft layer should have reasonably high permeability and have a thickness saturation-magnetization product similar to the thickness remanence product of the hard layer.

Operation of keepered recording is best understood in terms of a "virtual gap" induced by the DC bias current applied during readback. The virtual gap forms in the soft layer in a region under the head gap where the applied bias field is strong enough to saturate the soft layer as shown in Figure 1. The incremental permeability in the saturated virtual gap is very low and, from the perspective of the signal flux from the hard layer, it appears as a magnetic gap. This virtual gap is

fixed in position relative to the head as it scans over the recorded data. The resulting geometry may thus be thought of as a composite head made up of the ring head plus the soft layer with its virtual gap. This composite head has infinitely long pole lengths and is in very close contact with the recording medium. In theory therefore, the readback spacing loss is negligible. The overall efficiency of the composite head is reduced by the reluctance of the two additional internal gaps (between the keeper and the pole-tips). If the keeper is highly permeable and the pole-tips are long the reduction in efficiency will be small.

B. Write Process

In keepered recording, the analysis of the write process is complicated by the saturable, soft magnetic keeper layer. Ideally, a complete, self-consistent write model, incorporating head, keeper, and recording layer behavior should be used. Considerable insight can be developed by using a simpler, Williams-Comstock [16] approach to find the final arctangent transition parameter, a_2 . First a_1 is calculated, this is the initial "a" parameter still in the presence of the head writing field. The value a_1 then relaxes to a_2 as the transition moves away from the head. In ultra-high density recording applications, a_1 is limited by the head field gradient at the center of the recording layer at the point where the transition is written, which is where the head field equals the coercivity. It is assumed that the keeper layer has very little effect on this initial write process because it is heavily saturated in the vicinity of the transition. The keeper layer, however, will significantly affect the relaxation from a_1 to a_2 . Normally the transition's own demagnetizing fields will cause it to broaden as it moves away from the head. In the presence of the keeper layer, the demagnetizing fields are significantly reduced and the relaxation from a_1 to the final a_2 is less pronounced.

Modifying the augmented Williams-Comstock derivation (Eqn. (5) in [17]) to include the presence of the keeper, we get the following equation which can be solved iteratively for a_2 :

$$\frac{a_2}{a_1} = \frac{1 + 2\pi \cdot \chi \cdot t \cdot \left[\frac{1}{a_2 + \frac{t}{2}} - \left(\frac{\mu - 1}{\mu + 1} \right) \cdot \left(\frac{1.5 + \frac{\beta}{t}}{a_2 + 1.5t + \beta} + \frac{.5 + \frac{\beta}{t}}{a_2 + .5t - \beta} \right) \right]}{1 - \chi \cdot (1 - S) \cdot \frac{H_c}{M_r}}$$

where $\chi \equiv M_r/4H_c$ is the Williams-Comstock approximation for the minor loop susceptibility of the recording layer, t is the hard layer thickness, μ is relative permeability of the keeper layer, β is break layer thickness, and S^* is the coercivity squareness of the recording layer.

Figure 2. Illustrating the origins of the time and amplitude asymmetries in keptered recording.

It is assumed that the keeper layer is infinitely thick, and the image fields from the keeper are determined by Potter's expression for the field from an arctangent transition [18].

Assume a 15 nm keeper with permeability of 100, a break-layer of 1 nm, and a typical 100 Kbit/inch inductive head recording system: $M_r t = 1.9$ memu/cm² ($M_r = 560$ emu/cc, $t = 34$ nm), $H_c = 2000$ Oe, $S^* = 0.8$. Because of the thickness of the keeper and break layer, the initial a_1 parameter is 66 nm for keptered recording vs. 59 nm for no keeper. However, after the relaxation, from (1), we have $a_2 = 73$ nm for the keptered medium vs. 74 nm for no keeper. The additional spacing caused by the keeper is thus almost exactly counterbalanced by its effectiveness in reducing the subsequent broadening of the transition.

C. Read Process

The two basic approaches for analyzing the read process, reciprocity and direct calculation of read flux in the head, are also applicable to keptered recording.

Analysis by reciprocity requires linearity. Because the keptered recording system is inherently non-linear, the read process must be linearized by a small-signal expansion about the bias current, I_{bias} . Using a simple finite difference model, Gooch, et al., [2] calculated $\partial H_x(x)/\partial I_{bias}$ around the optimum bias point and showed significant sharpening of the small-signal head sensitivity function.

Study of the large-signal read process involves direct calculation of the flux in the head while including non-linear saturation effects in the keeper layer. Loven, et al., [9] used a non-linear boundary element method to study readback pulses from isolated step transitions of magnetization in a longitudinal recording medium. They found that the pulse sharpening of keptered recording observed by Gooch, et al., can be accompanied by time-shifts and time asymmetries. Work by Coughlin et al. [19,20] also revealed asymmetric pulse amplitude.

Figure 3. Isolated pulse responses for keptered vs. unkeptered media (copyright 1993 IEEE [7])

These nonlinearities are apparently caused by the relatively large fields produced in the keeper layer by the recorded transition, Figure 2. The longitudinal component of these fields changes sign at the transition location. Consequently, it adds to or subtracts from the bias field to change the shape and location of the virtual gap. The result is a disturbance of the readback pulse timing and amplitude depending on the sign and location of the recorded transitions. Mian, et al. measured the timing shifts in a keptered recording system using time-domain correlation techniques and found the shifts to be a significant fraction of a bit-cell [8]. More recently, Wilson, et al. have modeled these effects as arising from a signal-dependent modulation of the head efficiency. Based on this model, they have been able to derive an effective nonlinear equalization technique [11].

III. STRUCTURE AND FABRICATION OF KEPPERED DISKS

Keppered disks are typically composed of a conventional longitudinally-oriented hard medium overlain by a magnetically soft (high permeability) layer. The soft film is deposited by RF or DC magnetron sputtering. Early longitudinal keptered media work was done using permalloy (NiFe alloy) films [2][21][8]. More recently, very thin DC or RF magnetron sputtered films of Sendust (Fe-Si-Al alloys) have been found to give better performance [22][19][20][23]. Other soft magnetic materials have been explored as keeper layers including Co-Zr-Nb alloys[10]. It has been found to be beneficial to have a non-magnetic layer between the hard and soft films.

Figure 4. Amplitude, PW50, and timing as a function of bias MMF. (after [19])

This "exchange break" ensures that the soft film has low coercivity (high permeability) and responds only to magnetostatic coupling. Typical materials include DC magnetron sputtered Cr, C or Si or RF sputtered insulators such as Al_2O_3 . A layer as thin as 1.5 to 3 nm is found to be effective.

The best inductive head performance is observed when the saturation-thickness product, $M_s t_k$, for the keeper is comparable to or slightly less than the remanence-thickness product of the hard layer, $M_r t_h$. Sendust films which have been circumferentially oriented are found to give more output than radially oriented films. Measured coercivities, which are around 40 Oe on a magneto-optical magnetometer, are several times higher than for similar films deposited without the hard layer.

Figure 5. Readback signal vs. displacement off track for kept and unkept media. The density is 400 flux-changes/mm. The head has a track width of about 3 microns.

IV. INDUCTIVE HEAD MEASUREMENTS AND RESULTS

A. Linear Density Effects

Figure 3 compares isolated pulses for kept vs. unkept media used with an inductive head (from Kao et al. [7]). This early work illustrates several features which quickly attracted attention: larger signals, better resolution, and the elimination of the troublesome "undershoots" for the outside edges of the poles-tips.

The gains from kept recording are a strong function of the bias field. Figure 4 shows the gain in amplitude and resolution as a function of bias. This figure also shows that the gains are accompanied by significant asymmetries in amplitude and timing. At zero bias there is only a very small diffuse response. As the bias is increased, the readback pulse starts to rise but exhibits large timing asymmetry. As the bias is increased further, the PW50 reaches a minimum and the amplitude reaches a maximum. Just beyond this point, the asymmetry becomes smallest and the best system error-rates are obtained.

B. Off-Track Effects

During writing, the fields near the head-gap are largely unaffected by the presence of the keeper, which saturates heavily. Off the sides of the head, however, the reluctance of the intervening air gap and the shunting effect of the keeper cause the fields to drop more rapidly than normal. Measurements of track-profiles reveal a reduction in write-width of 5% [20]. More significantly, the side erase-bands [24] have been measured to drop by a factor of two (see section VII B).

Figure 6. "747" curve showing off-track capability vs. adjacent-track squeeze for a PRML channel. The kepted disk is tested at 137 kbp/s versus 112 Kbp/s for the unkeepted (after [20])

On readback, it has been noted that the virtual gap for an inductive head has a finite width (cross-track) as well as length (down-track). Off the ends of the virtual gap the keeper is unsaturated and highly permeable and might be expected to significantly reduce sidereading in a similar manner to that proposed by Mallory [14] although with an over-layer keeper. Figure 5 is a plot of sidereading attenuation vs. displacement off track for kepted and unkeepted media. The head has a track width of about 3 microns. In the region of interest, 20-30 dB of attenuation, however, the level of sidereading is only reduced by about ~1.5 dB.

C. Measured Areal Density Improvement

Error-rate measurements with peak detect channels have shown linear density improvements of 20% for kepted media [20]. For a PR4ML channel, Figure 6 shows a so-called "747" off-track margin plot [24] for kepted and unkeepted media at a 10^{-5} bit error rate [20]. Although the kepted media is recorded at 23% higher linear density, its off-track margin and squeeze failure point are the same or better than for unkeepted media. The head is a 42-turn planar head with a gap-length of 0.2 μm , a track-width of 3.5 μm , and a 27 nm flying height. The disk is CoCrTa with a coercivity of 2200 Oe and a M_t of 2.25 memu/cm². The added keeper layer is 15nm of sputtered Sendust.

Figure 7 shows "bath-tub" error rate plots comparing kepted and unkeepted media for a 42-turn, thin-film proximity recording head taken on a spin-stand and detected with an EPR4 channel emulation. The head and disk parameters are the same as described above, except that the flying height is 25 nm and the track-width is 3.2 μm . The results are taken at 12 m/s. Gap-

Figure 7. Error-rate vs. off-track position with an EPR4 (0,4,4) channel for kepted and unkeepted disks. The kepted disk is operating at 24 % higher linear density than the unkeepted disk.

length is 0.2 μm . The results are taken with no adjacent interfering tracks - just a dc-erase background. It is to be noted that the kepted disk was evaluated at 24% higher linear density (constant velocity) and yet had the same off-track performance capability.

E. Nonlinear Equalization

As mentioned above, kepted recording exhibits distinctive nonlinear effects. If these could be compensated, the readback process could operate at lower bias currents where the gains in amplitude and resolution are greatest. Wilson et al. [11] have proposed using a non-linear equalization technique to correct kepted media timing and amplitude asymmetries. The readback waveform is first integrated, passed through a memoryless nonlinearity, then differentiated to recover a corrected version of the original waveform. Dipulse extraction before and after equalization show that this non-linear equalization technique eliminates almost all the nonlinear distortion. Figure 8 reproduced from [11] shows the Sampled Amplitude Margin plot [25] for a PRML channel before and after this linearization. An improvement of approximately 10% in margin is observed. Further results from Hoinville [31] suggest that the onset of partial erasure may be moved to higher density by the presence of the keeper.

V. OTHER KEPTED CONFIGURATIONS

Almost all the work done to date on kepted recording has employed an inductive ring head and has placed the keeper layer on top of the hard layer. There are, however, a number of other possible configurations which are also of interest: keeper layer under instead of over the hard layer, MR readback instead of inductive, perpendicular hard layer instead of longitudinal.

Figure 8. Sampled Amplitude Margin plot before and after nonlinearity correction (after [11])

It was acknowledged in the original work that the keeper may perform better underneath rather than on top of the hard layer [1]. For practical reasons of fabrication, however, all of the early work was done with the keeper layer on top of the hard layer. Only recently, in conjunction with MR heads (Section VII) has it been demonstrated that the “keeper under” configuration is also very viable.

With respect to magneto-resistive heads, one might suspect by analogy with the inductive ring head that a single-gap yoke type MR sensor should work well with kept media. However, it is not as clear that a conventional double-gap shielded MR head will work well. Again the recent results described in the following section show that good signals can be obtained from a conventional double-shielded MR head without any further special provisions for bias fields.

Perpendicular recording with a keeper also raises a host of possible configurations: single-layer, dual-layer, pole-head, ring-head, MR-head, keeper-over, keeper-under. However, none of these configurations seem particularly promising. Underlying all the options is the concern that the keeper will saturate heavily in the vicinity of a relatively isolated transition. In longitudinal recording the thickness of the keeper layer is chosen to just avoid the keeper becoming saturated, i.e. $M_{s,t,soft} > M_{r,t,hard}$. For perpendicular recording, however, the flux flowing back across an isolated transition through an ideal non-saturating soft film would tend to infinity. It is thus likely that the readback process would be highly nonlinear. No work on kept perpendicular media has yet been reported.

VI. MR HEAD MEASUREMENTS AND UNDERLAYER KEEPER RESULTS

The theory of a virtual gap can also be applied to readback with a conventional double-shielded soft-adjacent-layer magneto-resistive element. Acting as a one-turn head, the normal levels of MR bias current should create sufficient field across the gap between the shields to saturate the keeper layer. In this case however, the unsaturated areas of keeper either side of this virtual gap are now effectively extensions of the shields. The equivalent magnetic structure is now an MR head with its shields in contact with the hard recording layer but with a deeply recessed sensor. Furthermore, in contrast to an inductive head, the virtual gap will extend the full width (across-track) of the shields and will thus be much greater than the width of the MR element. With this model in mind, we expect MR heads to show similar improvements in resolution but to have reduced output levels and to show no improvement in sidereading.

Tests with MR heads confirm that signals can easily be recovered from conventional “overlayer” kept media at normal bias currents. The observed improvements in resolution are not large but neither are the reductions in amplitude. Interestingly, as for inductive heads, we have observed similar reductions in effective written track width on the kept media.

As indicated above, the keeper layer can be either above or below the hard magnetic layer. With MR heads, better results have been obtained with the keeper below the hard layer. Figure 9 shows that significant reductions in PW50 can be obtained with no loss in amplitude. These results were obtained with and without an underlayer keeper with an $M_{s,t,k}$ of 0.7 memu/cm². The hard layer was CoCrTa with $H_c=1800$ Oe and $M_{r,t}=0.7$ memu/cm². An MR head with a wide shield-shield gap of 1.1 μ m was used. An 18% reduction in PW50 can be seen with the underlayer keeper. The reduction of the skirts of the isolated pulses is even larger. Improved noise performance is also observed with the reduction principally at lower frequencies [26].

VII. SCALING AND RECORDING LIMITS

There is a fundamental limit to recording density known as the superparamagnetic limit. At this limit, the thermal activation energy is comparable with the energy required to switch the magnetic grains of the recording medium. In this situation, the recorded information will decay rapidly with time [27]. This decay is more severe if there are large internal demagnetizing fields within the

Figure 9. Isolated pulses for MR readback of kept media where the keeper layer is placed below the hard recording layer.

medium. The limit does permit a trade-off between signal-to-noise and ultimate density. Because of this, it is found more advantageous to operate on very narrow tracks at low bit aspect ratios [30].

A. Thermal Stability

To obtain large outputs from traditional recording systems every effort is made to maximize the field strength coming out of the surface of the medium.

Unfortunately, high external fields imply high internal demagnetizing fields. In both vertical and longitudinal systems the internal fields approach the coercivity of the medium. It is quite easy therefore for the recorded patterns to demagnetize further under the influence of stray fields, mechanical stress, or, in the ultimate limit, just due to thermal activation [27].

In contrast, the storage mode for kept recording is intrinsically very stable. Large demagnetizing fields are only present during writing and reading. At all other times the keeper layer acts to dramatically reduce the demagnetizing fields.

Figure 10 shows thermal decay rates for kept and unkept media measured by J. Chen et al. from the University of Minnesota [10]. The results were taken at 5000 flux-changes/mm on media with a low M_t of 0.6 memu/cm². The unkept media shows a decay in signal of 2.8% per decade of time vs. 1.1% per decade of time for the kept media.

Figure 10. Measured thermal decay for kept and unkept 0.6 memu/cm² Mrt media at 5000 frpmm (150 kfc). (copyright 1997 IEEE [10])

B. Bit aspect ratio

The so-called "side-erase-band" [24] is an important attribute of longitudinal magnetic recording. The absence of this erase-band has been cited as one of the reasons that perpendicular recording has not been adopted commercially [28]. However, for conventional longitudinal recording at very low bit aspect ratio, the erase-band may become proportionately too wide since it tends to scale with linear-density rather than track density. Kept recording offers a significant reduction in the width of the side erase band and is thus very compatible with recording at low bit-aspect ratio and very high track-density.

Measurements, using 120 mA pk-pk into a 15 turn head with a 0.7 micron gap showed a reduction in side-erase bands from 0.46 micron to 0.24 micron in going from unkept to kept media. This result was measured at 1700 flux-changes/mm using the triple-track profile technique [32]. The medium had a coercivity of 1450 Oe and an Mrt of 0.8 memu/cm².

VIII. CONCLUSIONS AND OUTLOOK

Kept recording is a novel recording technique about which there is undoubtedly still much to learn. The technique takes advantage of the nonlinear properties of a soft film which is incorporated into the medium. This approach opens up possibilities for increasing the resolution of the readback process in both the along-track and across-track dimensions. With inductive heads, significant improvements in resolution and performance have been demonstrated as well as small improvements in the cross-track direction. With

magneto-resistive heads the best results are being obtained with an underlayer keeper. There are a variety of other possible configurations and ways in which keepered recording might play a role. As well as offering superresolution and reducing the effects of readback spacing, perhaps the most exciting aspect of keepered recording lies in its potential at very high density. The lower rates of thermal decay and the smaller side erase-bands suggest that keepered media may be able to play an important role in extending magnetic recording to the highest areal densities.

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