Characteristics of noise in very thin advanced metal particle data storage tapes: an indication of interface roughness.

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Abstract: Advanced metal particle magnetic tapes, which have a magnetic top coat on a non-magnetic under layer, are used for archival applications of data storage. Increasing storage requirements dictate a move to greater bit density which requires smaller particles, higher coercivity and thinner magnetic coatings. This affects the noise characteristics of the tapes and in particular the media contributions. Measurements have shown that for thin magnetic coatings, the magnetic/non-magnetic interface roughness contributes to the noise and can cause an increased saturation noise. This indicates that interface quality is of major importance in producing low noise tapes and may be a limiting factor in future generations of thinner tapes. The dc noise characteristics are also a useful non-destructive indication of interface quality.

1. Introduction
In support of the rapidly developing dependence of society on information storage, retrieval and communication, the continuing demand for bigger storage space and faster data transfer rates is pushing the limits of the technology. Data storage must be seen as a complete package of different formats and technologies which are mutually supportive and fulfil specific roles. Whilst many data storage applications have migrated to magnetic hard disk (HDD) and optical systems (CDR etc.), magnetic tape continues to dominate the archival of data on large computer systems. There are a number of tape formats using linear and helical scan arrangements, but the dominant systems use ½” tape with multi-track linear recording. Two examples of such systems are LTO and super-DLT. This framework of archival and backup of data necessitates discrete units of high capacity, relatively fast writing and readout, compact volume, interchangeability between media and drives, long life of stored data and low unit cost. All such systems have their own characteristics related to the manufacturers or consortia that support them. However, the overall requirements of tape systems are determined by the computer storage applications and are continually changing and moving to higher data densities and faster access. These changing requirements are road mapped by the Information Storage Industry Consortium (INSIC) [1]. These road maps predict the requirements and system parameters that will be required over a period extending up to 10 years hence and are regularly updated and published [2].

There are two types of modern tape, metal evaporated and metal particle. The latter is the predominant type and consists of metal particles embedded in a non-magnetic binder system and coated onto a substrate. Currently, the coating consists of a double layer with a thin magnetic coating on top of a non-magnetic undercoat, both being laid down at the same time and dried as an entity. The
thicker undercoat has properties which aid the coating process and it also acts as a reservoir for lubricant. As tape density requirements evolve, the property requirements change. Particles evolve to generate higher anisotropy, smaller volume and the magnetic coating thickness is reduced. All current commercial systems use acicular iron particles with additional elements to increase anisotropy and to passivate the particles. As the tape parameters change, this has an effect on the recording properties. Whilst a thinner magnetic coating and higher coercivity are necessary to increase data bit density, this reduces the number of particles associated with each recorded bit and will effect the media contribution to noise. This aspect of tape properties is the subject of this paper.

2. Noise Studies

Noise is the limiting factor of data recording density and in modern media, this is dominated by media noise [3]. The media contributes to the noise in a number of ways. For example, the interaction between the head and the magnetic tape surface contributes to the signal side band noise [4] whereas the structure of the media contributes to the intrinsic broad band noise. Separating noise components generated by the recording process from the intrinsic media noise is difficult. Thus, we have used a technique where the noise is observed as a function of the remanent state of the tape in the absence of a signal [5]. Here the intrinsic media noise characteristics can be observed as a function of changing remanent state.

Media noise is directly related to the statistical variance of a magnetic state. In a simple idealised system of identical perfectly aligned non-interacting particles, we can calculate the noise from this variance. In the saturated state, there is only one possible arrangement of the magnetic moments which are all aligned and so the noise will be zero. In the dc demagnetised state, there are many arrangements with half the particles magnetised in one direction and the remainder magnetised in the opposite direction. All these arrangements will be sampled by the read head as it passes over the tape. In the general case when \( n \) particles of a total sample \( N \), each with a magnetic moment \( \mu \), are magnetised in one direction, then the variance is given by the simple binomial calculation [6].

\[
\sigma_n^2 = 4\mu^2n\left(1 - \frac{n}{N}\right) \tag{1}
\]

In other words, the saturation noise will be lower than that of any other magnetisation state. In practice systems are not that simple and the easy axis alignment, particle volume distribution will all increase the total noise. Furthermore, interactions play an important part in the noise. In any real system clustering of particles will cause flux closures in certain micromagnetic configurations and this can give rise to a decrease in noise [7]. This can lead to a situation where the saturation noise is higher than that of any other magnetisation state which is contrary to that of the idealised particle system.

From a combination of experimental measurements and computational simulations, we have previously identified the noise characteristics of particles in a tape and related them to their spatial distribution [8], which is primarily related to the local interactions associated with a particle. Essentially, the magnetic tape coating can be divided into three layers: the top surface; the bulk and the bottom surface, which is the interface between the magnetic and non-magnetic coatings. The bulk consists of particles which have near neighbours equally distributed around them such that the total inter-particle interactions are demagnetising in the dc demagnetised state. This generates the flux closure states mentioned earlier and results in a dc demagnetised noise which is less than that of the saturated state noise. The particles at the two surfaces, provided the surfaces are smooth, have mean inter-particle interactions modified by the distribution of the neighbours and which does not produce the flux closures so that the noise characteristics and are more like that of an idealised particle system with the dc demagnetised noise greater than that of the saturated noise state. Roughness on the surface has the effect of introducing asperities which behave like large magnetic structures and can also form flux closures and noise characteristics similar to the bulk particles.
Our studies on modern, but relatively thick tapes have shown that their noise characteristics change as the tape magnetic coating gets thinner. For the thickest samples (coating thickness ~300 nm) the behaviour is dominated by particles in the bulk and the saturation noise is higher than that of the dc demagnetised state. As the tapes become thinner, the contribution of the bulk particles is reduced and the characteristics are dominated by the top surface and the dc demagnetised noise is greater than that of the saturated state (modern tapes are sufficiently smooth so that asperity effects are not observed). Recent experiments have examined thinner tapes which have been produced on pilot plant and intended for laboratory investigation rather than for production applications. The investigation has involved a series of four tapes produced using the same advanced metal particles (referred to as type MP3), dispersed and coated in the same manner but with different coating thickness. The basic parameters are given in table I.

| Tape sample | $\text{Mrt \ (memu/cm}^2\text{)}$ | $\text{Hc \ (kOe)}$ | Squareness | Thickness \ (nm) |
|-------------|-------------------------------|------------------|-------------|-----------------|
| MP3 (A)     | 3.4                           | 2.56             | 0.84        | 140             |
| MP3 (B)     | 2.3                           | 2.56             | 0.83        | 100             |
| MP3 (C)     | 1.7                           | 2.52             | 0.82        | 70              |
| MP3 (D)     | 1.9                           | 2.58             | 0.82        | 80              |

Table I: Basic magnetic parameters of a series of four tapes studied.

Noise measurements were made on the samples using an open reel bench tester on which parameters such as speed, tension and direction of motion could be controlled. The system was fitted with a slotted yoke electromagnet so that the tapes could be subjected to a known in-plane magnetic field to create a specific remanent state and was used in the experiments described here to initially saturate the tapes. Subsequent conditioning was performed using a the write head element of head designed for an LTO tape drive and consisting of a write head element and an MR read head element. The noise was measured using the read head element and the observed signal was analysed using a LeCroy digital storage oscilloscope with a built in FFT software function to generate the spectral features of the noise. The tapes were run at a tension of 1 N and a speed of 2 ms$^{-1}$ and they were taken through a remanence cycle corresponding to the dc demagnetisation process going from positive to negative saturation.

![Figure 1 Spectral noise map showing the variation of noise power with dc remanent state for MP3(A) and MP3(B) when taken through the dc demagnetisation process from positive to negative saturation.](image)
There was a marked difference between the noise spectral maps of samples MP3(A) and (C) and those of MP3(B) and (D). Figs 1 (a) and (b) show the spectral maps of MP3(A) and MP3(B). The maps show the spectra of the noise power as wave number related to the density on the tape and how they vary as the tape is slowly demagnetised, taken through the dc demagnetised state (remanent coercivity) and to saturation in the opposite direction. Spectral noise maps for MP3(C) and MP3(D) show a similar difference and so are not reproduced here. There are a number of features which should be noted:

a) With the exception of the initial saturation state, all remanent states were generated using the writing head and indicated by the head current on the maps in fig. 1. This means that field gradients and field rotation was applied to the tape in generating these states so that the final saturation state was not identical to the reverse of the starting state. This is apparent in the noise spectra and it can be noted that the starting noise levels are higher than the final values.

b) There is a dramatic difference between variation of noise with remanent state between MP3(A) and (B). This same difference was observed between MP3(C) and (D).

c) It should be noted that the noise power axes in figs. 1 (a) and (b) are on different scales and that the noise power level of the peak in fig. 1 (a) is at about the same level as the bottom of the valley in fig. 1(b). This suggests that MP3(B) has a massive noise power associated with saturation which dominates and masks all other noise features in this tape. The same conclusion could be drawn for MP3(D) in relation to MP3(C).

Figure 2: Spectra of a recorded tones for MP3(A) and (B) measured at a tape speed of 2.5 ms⁻¹ showing very similar broad band and side band noise characteristics.

Figure 3: DC saturation noise for MP3(A) and (B) showing a large peak at low wave number for MP3(B).

Figure 2 shows a comparison of spectra for MP3(A) and (B) of a recorded square wave or tone. It can be seen that the characteristics are very similar and there is no evidence of the high noise associated with saturation. Figure 3 shows the dc saturation noise for the same two tapes extracted from the spectral maps of fig. 1. It can be seen that the major noise component at saturation in MP3(B) is dominated by low wave numbers.

The question arises as to why there is such a significant difference between the dc noise characteristics of the samples even though this is not observed in the tone noise measurements. Since wave number, or wavelength on the tape, is related to the size of magnetic structures involved, our estimation is that the saturation noise in MP3(B) is related to magnetic structures of size centred on ~40 µm. This is very large compared to particle lengths which will be ~100 nm. These tapes have a magnetic coating thickness in the range ~70 - 150 nm which is of the same order as the particle length. Even given the particle aspect ratio of about 6:1, the coating will only be a few particles thick and we would therefore expect these tapes to have media noise dominated by the surfaces. Since the side band noise is the same for MP3(A) and (B), this seems to suggest that the top surfaces are similar [4] and this is in line with mechanical measurements on the tapes. This would therefore suggest that the large magnetic structures are associated with the magnetic/non-magnetic interface.
Because of the long length scale of these magnetic structures, when a square wave of shorter length is recorded, there will be many flux reversals within the length of one structure and this will demagnetise them so that the high noise will be suppressed as a result of the flux closure that will be produced by the demagnetisation.

To try to confirm this opinion, we have simulated the effect of interface roughness using the model described in ref. [8]. A sample consisting of 6316 spherical particles was constructed using a gradual variation of thickness between 1 and 5 particles. Figure 4 shows an insert (a) of the surface which, although shown on the top in the insert, is at the surface furthest away from the writing and read heads. The simulation involved generation of remanent states following the dc demagnetisation process from positive to negative saturation using a solution of the Landau Lifshitz Gilbert equation and then acquisition of the read head time series by measuring the vertical components of the stray field at intervals along the tape and integrating to determine the MR read head response. The spectral noise map in fig. 2(b) is the simulated response and can be compared to (c) which is the response with a smooth interface. It can be seen that the introduction of interface roughness does reduce the noise in the dc demagnetised state and also increases the saturation noise level at low frequencies.

3. Conclusion
All the evidence suggests that tape samples MP3(B) and (D) have an interface roughness on a length scale of 40 μm which is not present in samples MP3(A) and (C). Although this does not have an effect the broad band or side band noise observed in our measurements at normal recording densities, it is likely that this would not be the case if the wavelength on the tape were increased. In fact, initial studies of this indicate that this is so. Whilst this does not affect use of these tapes for current recording, as tapes get thinner (and thus the interface gets nearer to the read head) effects are likely to become more dominant. Length scales will also change and it is possible that this may become a limiting effect in future generations of tape. Whilst it is possible to control top surface texture and also to observe its characteristics directly using imaging techniques, the magnetic/non-magnetic interface is difficult to observe and is also difficult to control using current technology as the two coatings are laid down wet and are dried together. These measurements therefore suggest that it is important to develop coating
technology so that the interface smoothness can be controlled. Additionally, since the dc demagnetisation noise measurements appear to be very sensitive to interface roughness, they provide a useful non-destructive measurement of interface quality.

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