Error Rate Drift Caused by Rubbing Noise in Ferrite Read Heads

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Abstract

Some combinations of DDS-3 tape drive and cassette experience a rapid increase in error rate, followed by a gradual spontaneous recovery, when a section of tape is repeatedly used. This behaviour is caused by a change in the level of rubbing noise resulting from changes to the surface of the read head. This paper describes an investigation into the nature of this noise, and in particular the effect of head-tape speed on its frequency spectrum. In some cases, standing-wave vibrations in the head structure are excited by periodic ripple features that form on the surface of the ferrite read heads.

Keywords: *magnetic recording, tape, friction, noise*

Introduction

As part of an ongoing quality assurance program, Hewlett-Packard's Digital Data Storage (DDS) helical-scan tape drives are subjected to rigorous tests. In mid-1998 some DDS-3 drives were found to experience a progressive increase in their uncorrected error rate when subjected to a particular test, known as "maggot". A gradually worsening error rate of this kind is known colloquially as "error rate drift". Although the DDS format's error correction protects the end user from being affected by this degradation, HP wanted to understand the phenomenon in order to eliminate it, and so reduce its impact on the drive's margin to other impairments.

For error rate drift to occur two things are needed:

1. an impairment that causes the error rate to increase
2. a mechanism that systematically increases the level of this impairment

Error rate drift had previously been observed when HP's DDS-2 tape drives (an earlier product) were operated in low humidity conditions[1]. In that case the impairment was identified as a layer of contamination that transferred from the tape to the surface of the read heads, whilst the mechanism was identified as the reduction in abrasivity of the tape each time it interacted with the heads. This caused the "stain" thickness to increase each time a section of tape was reused, resulting in a progressive increase in spacing loss, and an attenuation of the readback signal amplitude. Was the error rate drift seen in the maggot test caused by this staining mechanism?

Initial Observations

The maggot test performs a complicated sequence of tape movements, in the process of which some sections of the DDS-3 metal particulate (MP) tape are reused many times. As a first step in our investigation a greatly simplified test was devised in which the drive wrote 768 frames (~ 12 seconds) of random data to a section of previously unused tape, and the read-after-write (RAW) error rate was measured. Using the drive's tape counter as a guide, the tape was then rewound to the starting point, and the same section of tape was overwritten. This write-rewind process was repeated 200 times over the same section of tape, producing the first region of drift shown in figure 1.

After 200 reuse passes the tape was moved forwards at the normal recording speed for 5 minutes, so that unused tape passed over the write and read heads. This resulted in a gradual fall in the error rate, until it returned to its initial level. The recovery is shown in detail in figure 2, but is simply represented by a vertical line in figure 1 (the *x*-axis of

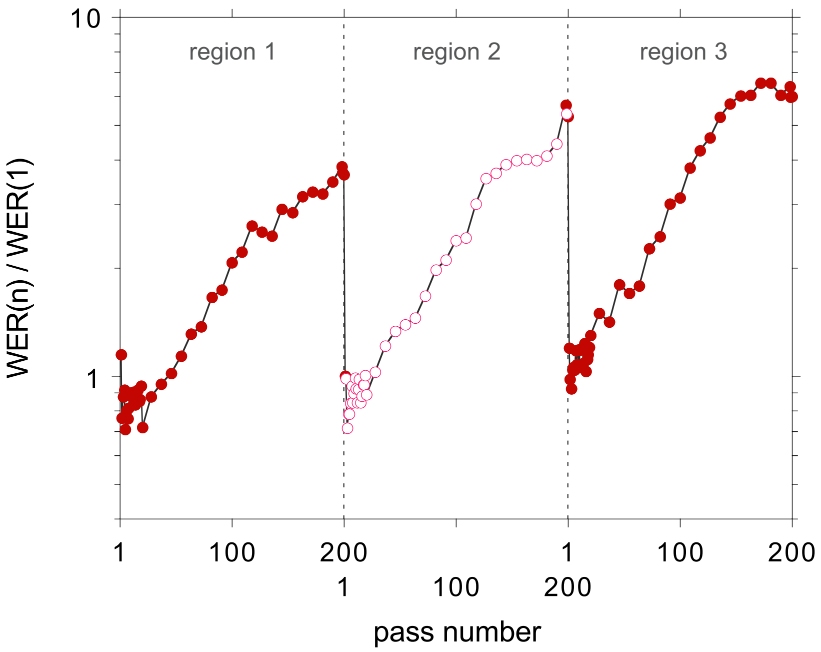

Fig. 1 "Error rate drift" in the uncorrected read-after-write error rate (solid), and read error rate (open), normalised by the first measured value (2.1e-3). The sequence of operations yielding this behaviour is described in the text.

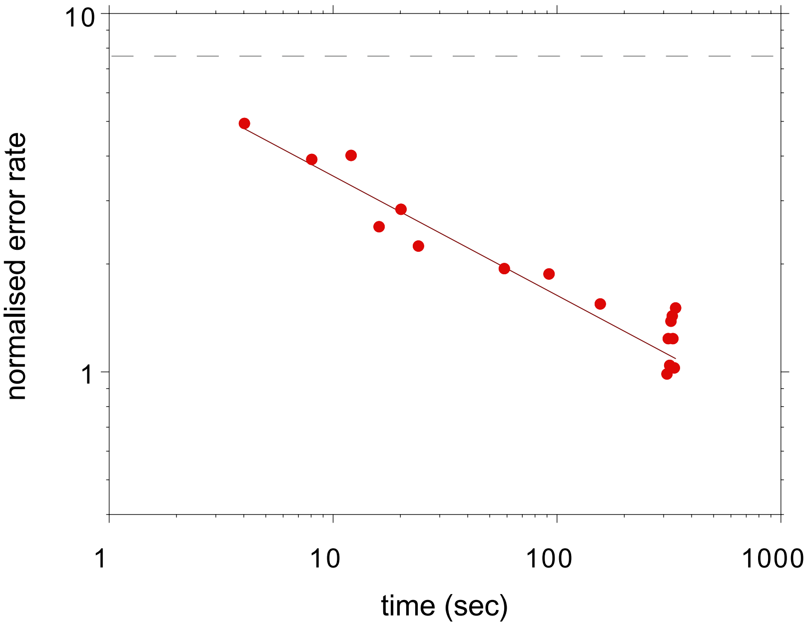

Fig. 2 Recovery from error rate drift by pulling unused tape for the time shown. Points show the uncorrected read-after-write error rate normalised by 2.1e–3. Dashed line shows error rate before recovery. Solid line shows $y = 7.6/\sqrt[3]{t}$.

which is not time, but pass number). The gradual recovery probably results from abrasive wear of the head by the rough unused tape, and indicates that the underlying impairment is associated with a change to the surface of the head, rather than the tape.

The second region of drift in figure 1 starts on unused tape. During the first pass over this, data was written and the RAW error rate was measured. In all subsequent passes, however, no writing took place, but the data was read and the read error rate (RER) was measured. This produced almost exactly the same drift behaviour as seen in the first drift (RAW), indicating that the drift is dominated by an impairment to the reading process.

On completing the second drift, the error rate was again lowered by pulling unused tape for 5 minutes. The third region of drift was then produced in an identical way to the first region.

Figure 3 plots the increase in error rate (known as “drift factor”) of the A-channel against that of the B-channel for 60 drives that had previously failed the maggot test. The weak correlation suggests that the process that causes drift affects both the A-channel and B-channel, but that the level of response depends on some property that is slightly different for the two channels - probably something associated with the heads themselves.

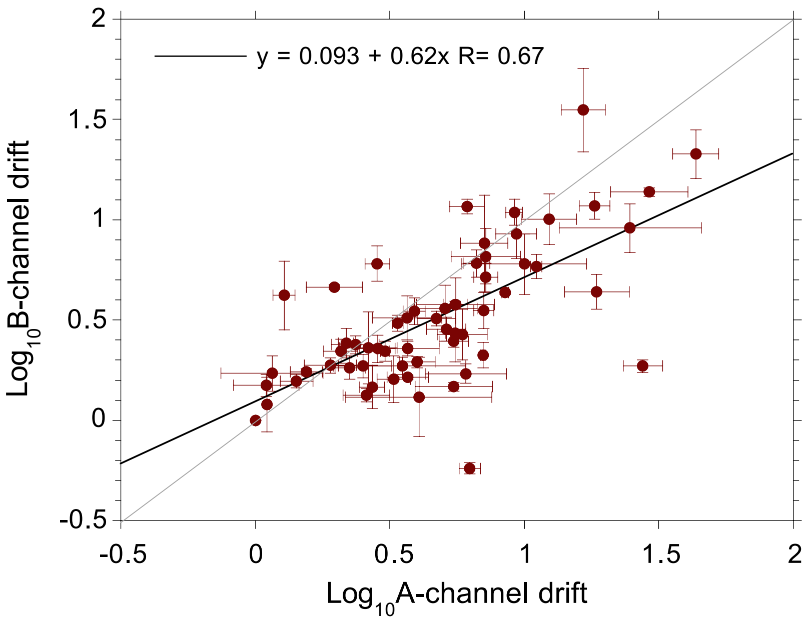

Fig. 3 Drift factors of A-channel vs. B-channel of 60 drives that had previously failed the "maggot" test. Points show the median of three measurements, whilst error bars show the standard error.

The similarity of the three drift regions shows that the drifting behaviour *was* reproducible within a single experiment. Moreover, it was observed that as more drift-recovery cycles were performed with a particular drive and cassette, consecutive drifts became increasingly similar. Repeating the experiment with the same drive and cassette but on a different day would produce a significantly different amount of drift. An even greater difference would be seen if the cassette was changed - even to another from the same batch. With different drive-tape combinations the extent of drift varied from 1× (i.e., no drift) to 30× when performing the 200-pass test.

The highly variable nature of the drifting phenomenon was consistent with experience from the manufacturing line, where drift had not been seen in the maggot test prior to mid-1998. A detailed investigation revealed that the occurrence of drift was strongly affected by the tape batch, with a smaller dependence on the manufacturing date of the drive, and an interaction affect between the drive and tape. Consequently, only some "bad" combinations of drive and tape batches produced problematic levels of drift. This suggests that the cause of error rate drift may be associated with an uncontrolled variation in material properties of both the tapes and the heads. Unfortunately we were unable to identify any change in either the tape (e.g., abrasivity, roughness) or the read heads that could be associated with the onset of drift in the maggot test.

Experiments were carried out to measure the effect of tape tension on the extent of error rate drift. These showed that lowering the tension reduces drift, and can even make the error rate improve as the tape is reused, probably because the tape surface is worn smoother and the head-tape spacing decreases[2]. Increasing the tension appeared to make the drift worse; however, detailed experiments revealed that as the tape tension is increased there is a gradual transition to dominance by a second, larger, and probably unrelated type of drift, caused by damage to the tape (appendix A).

The information presented so far is consistent with the previously encountered staining-based form of error rate drift; however, several observations were puzzling.

1. Significant drift in the maggot test had been seen at modest levels of relative humidity (RH ~ 40%), and spot checks on whether drift became worse at low humidity (10%) in the simple 200-pass experiment indicated that there was no affect. This was contrary to the drift caused by staining, which increased rapidly as the humidity was reduced below 30%[1].
2. An Atomic Force Microscope (AFM) was used to examine the heads from a drive that had just experienced large error rate drift in the 200-pass test (figure 4). The ferrite tape bearing surface was not covered with the 10-30 nm thick patches of

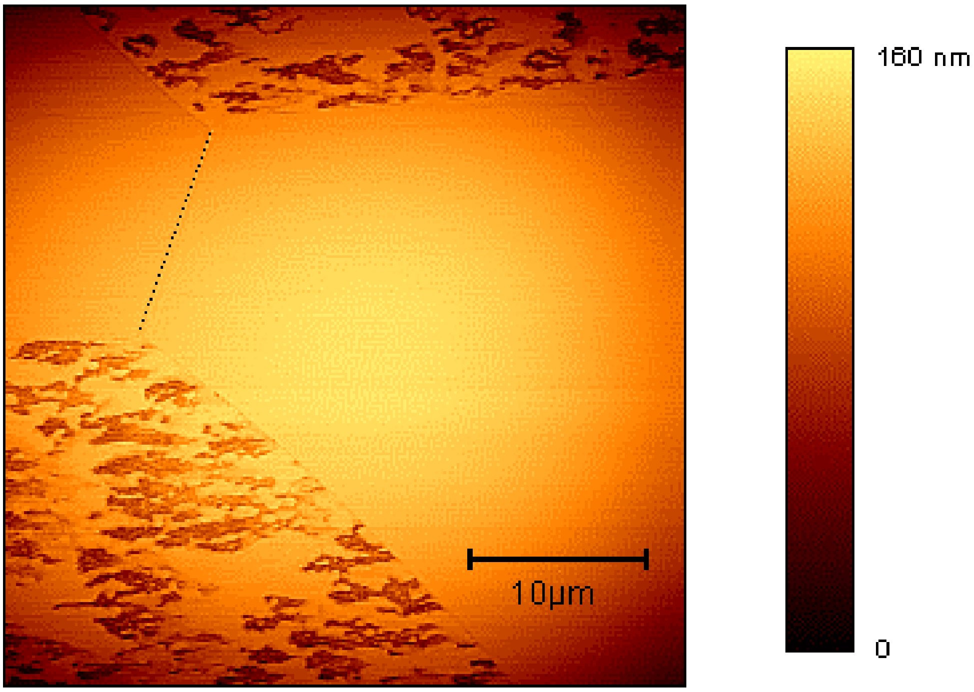

Fig. 4 Topography of a single crystal MnZn ferrite read head from a Hewlett-Packard DDS-3 tape drive. Measured with a Digital Instruments Dimension 3000 Atomic Force Microscope (tapping mode). The position of the gap is indicated by the dotted line. Tape makes contact with the entire region shown in this image.

contamination that are known to build-up during the stain-based drifting process[1]. Although stain was present on the glass, this is recessed with respect to the ferrite and, it is believed, does not contribute to spacing loss[1].

3. Measurements were made of the change that occurs in the signal-to-noise ratio (SNR) of a DDS-3 tape drive as the error rate drift took place. Unlike similar experiments with stain-based drift, there was very little attenuation of the playback signal amplitude, with the calculated channel frequency response indicating that no significant spacing loss was occurring. In fact the degradation in SNR, and hence error rate could be totally attributed to a gradual increase in incoherent noise.

The new evidence suggested that the impairment underlying error rate drift in the maggot test was not stain, but was a source of noise that somehow increased as the tape was reused. The next section describes experiments that were carried out to characterise this noise.

Measurement of Rubbing Noise During Drift

A spectrum analyser[*] was used to monitor changes in the output of the read head's pre-amplifier as error rate drift took place. On each pass over the media the RAW error rate measurement[†] was immediately followed by 20 seconds of blank tape. Spectra were measured from the data region and from the blank tape, and saved to the host computer that controlled the drive and instrumentation.

When no tape was present the output was solely from electronics noise. However, when blank (i.e., demagnetised) MP tape runs in contact over a ferrite read head, stress generated by friction creates, through inverse-magnetostriction, a change in the head's internal magnetisation. In turn, this generates a noise voltage in the head's windings, and hence a noise in the pre-amplifier output[3]. This so called "rubbing noise" can be clearly seen in figure 5 (top two curves), as the increase that occurs between the electronics noise, and the output with previously unused tape (pass 1). To clarify the terminology used in this paper, "blank-tape noise" is the total noise measured when pulling a.c. erased tape over the heads, and consists of rubbing noise plus electronic noise.

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[*] HP 3585B or HP 4395 spectrum analyzer, RBW = 30 kHz, VBW = 1 kHz, external gated trigger set to capture the central 3.0 ms of the data track

[†] 768 frames of DDS-3 format, random data

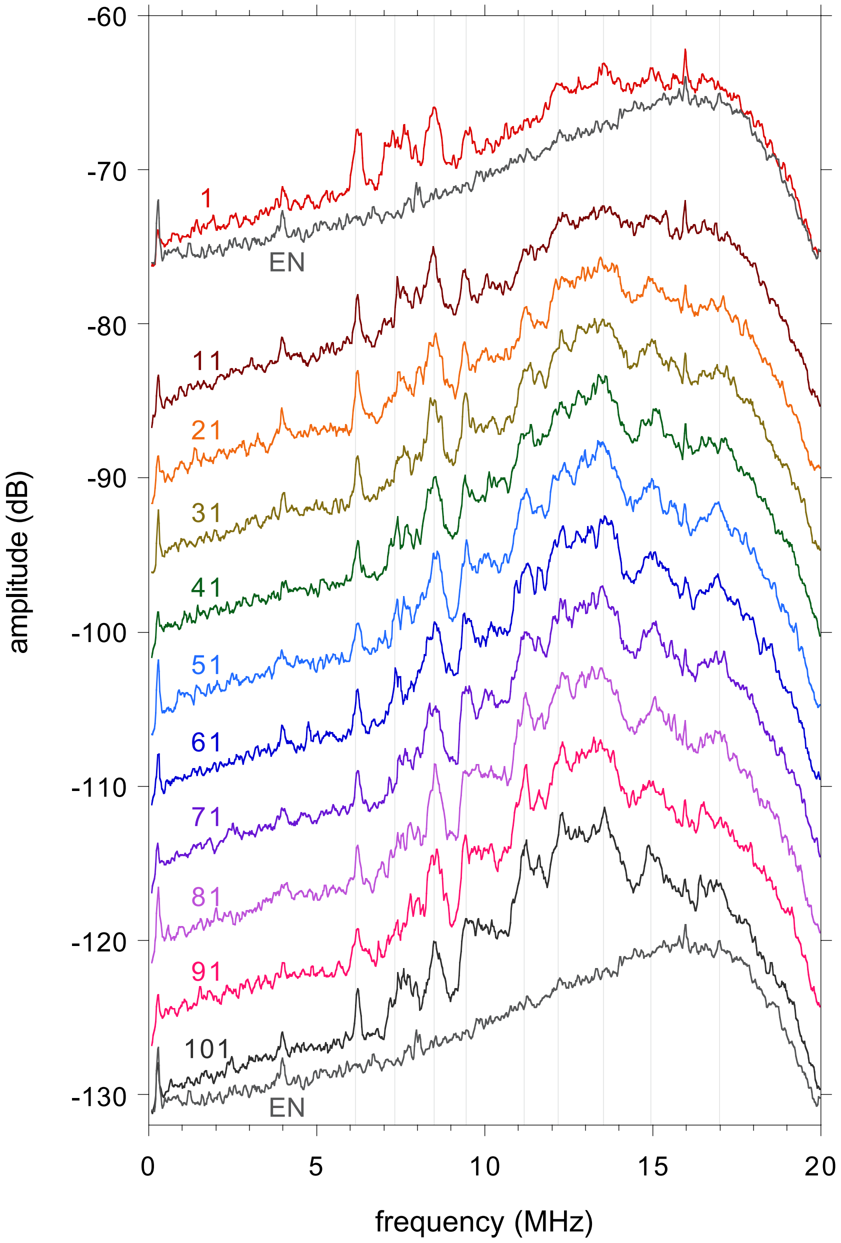

Fig. 5 Change in the blank-tape noise spectrum during 101 passes over the same section of tape. The curves are offset for clarity. Electronic noise spectra (EN) are shown for the first and last curves. Drive L509753, cassette 125M92N8M1, 45% RH, 21°C.

When the read heads first pass over previously unused tape the rubbing noise of some drives only contains a +2 dB background that extends from DC to about 17 MHz; however, most spectra also have several strong, sharp peaks at frequencies between 6.2 MHz and 9.5 MHz, and a few smaller broad peaks at higher frequencies.

Strong peaks in rubbing noise spectra are usually associated with distinct standing wave vibrations that are set-up in the head, at frequencies determined by the dimensions and acoustic propagation velocities in the head material[4]. Magnetostriction in the ferrite converts the oscillating change in dimensions into a changing flux, and so produces an induced noise voltage peak at the frequency of the standing wave. The read heads in a DDS-3 tape drive are composed of two non-identical, asymmetric halves, that are joined together to form the front and back gap. In addition, sections of the ferrite are removed to accommodate the windings, and other parts are thinned-down to define the gap width and increase the magnetic reluctance of the front gap. This complicated structure means that many vibrational modes are supported, and many peaks occur in the rubbing noise spectrum. Attempts are often made to identify a head's resonant modes from the observed spectral peaks[5], but this can only be done with confidence when using simplified gapless test heads[4]. Consequently, we have not attempted to make the identification.

The reproducibility of rubbing noise spectra was fairly good, with different measurements (made 8 months apart) of the same drive yielding peaks at identical peak positions and with similar magnitude. In contrast, rubbing noise spectra from different heads - even two heads from the same drive - have peaks at different frequencies (compare figures 5 and 8). This is probably caused by slight differences in their geometry resulting from manufacturing variation (e.g., tolerance in dimensions, different amounts of in-fill glass used) and differences in wear affecting their gap depth.

As the tape is reused there is no change in the frequencies at which peaks occur; however, the relative size of the peaks does change - with a large increase in the height of initially small peaks (and the background level) above 9 MHz.

A simple metric that can be used to quantify the total rubbing noise is the area contained between the curves of electronics noise and blank-tape noise, between DC and 20 MHz. This metric increases as the tape is reused, and is strongly correlated with the degradation that occurs in error rate (figure 6).

Whilst investigating this correlation, extended tests were performed in which more than 200 passes took place. Surprisingly, the error rate and noise metric were always found to gradually recover, and after many hundreds of passes over the same section of tape, they return to the initial value seen with new unused media (figure 7). The rate at which this spontaneous "self-recovery" occurs, and the position (i.e., pass number) of the maximum value of error rate, varies by a large amount from drive-to-drive, although they appear to be very reproducible characteristics of the drive under test. During self-recovery the error rate and noise metric remained correlated in the same way as during the preceding drift. Figure 7 also illustrates how the absolute noise metric of the two channels is always very similar in size.

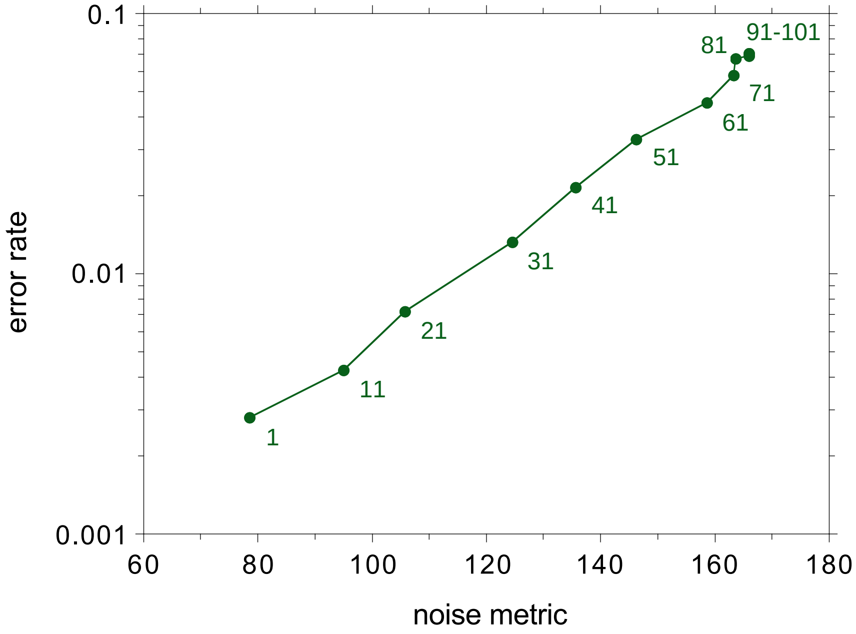

Fig. 6 Correlation between error rate and rubbing noise metric (dimensionless). Points are labelled with the pass number in which the measurements were made. Data were taken from the same experiment as figure 5.

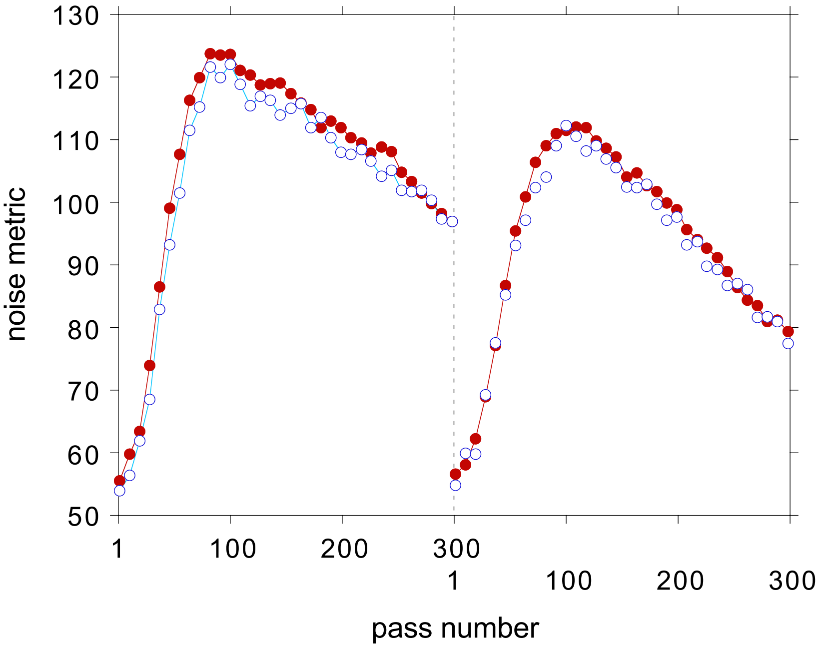

Fig. 7 Spontaneous gradual recovery in noise metric after 100 passes. In other drives the recovery may be much more gradual, and may start after 500 or more passes. Solid circles represent the A-channel. Open circles represent the B-channel.

Effect of Head-Tape Speed on Rubbing Noise

To confirm that peaks in the rubbing noise spectra are due to standing modes determined by the head's geometry, measurements were made to check that the peak positions were invariant when the head-tape speed was changed. Two approaches were used:

1. A section of previously unused tape was reused 101 times at a chosen "drifting speed", usually nominal, to develop a drifted state with large rubbing noise. The drum speed was then varied from 0.5× to 1.5× nominal, and at each new speed a spectrum was measured on the fifth pass over the well-used tape.
2. The speed was set to the desired value and a new 101-pass reuse script was started on unused tape. A spectrum was measured on pass 101, then the speed was changed to a new value and the system was reset to the undrifted state by pulling unused tape. This was repeated for speeds from 0.6× to 1.4× nominal.

In both cases the order of speed settings was randomised, and the measurements were repeated to check for reproducibility. The same behaviour was observed with both methods, although method 1 gave slightly less scatter due to their being a smaller change to the system between each measurement. Unless otherwise stated, all results presented in this paper are from method 1.

As the head-tape speed is increased, the frequencies at which peaks (i.e., local maxima) occur remains unchanged, as expected; however, the relative amplitude of the peaks and the shape of the background do change, so that the overall spectral shape changes (figure 8). This is different from result of Johnson and Huijer[4], where the height of all peaks increased to the same extent so that the spectrum grew but retained the same shape. In fact, this latter result can obtained if the drum speed is changed when drive is in an undrifted state, having just pulled unused tape for 5 minutes.

Inspection of figure 8 shows that as the speed is increased the location of the largest peak (global maximum) moves to higher frequencies. This change, shown more clearly in figure 9, occurs in a very uniform way until the preferred location of the highest peak moves above the roll-off frequency in the channel's transfer function (~20 MHz), after which any noise generated in the head will not be detected by the spectrum analyser. For the same reason, the total rubbing noise metric does not increase monotonically with increasing speed, but reaches a maximum at about 1× (i.e., nominal) speed, after which it decreases as the speed is further increased.

The behaviour shown in figures 8 and 9 suggests that as the head-tape speed is increased a speed-related vibration increases in frequency, exciting both the background and nearby modal frequencies in the head. The line in figure 9 shows how an increasing

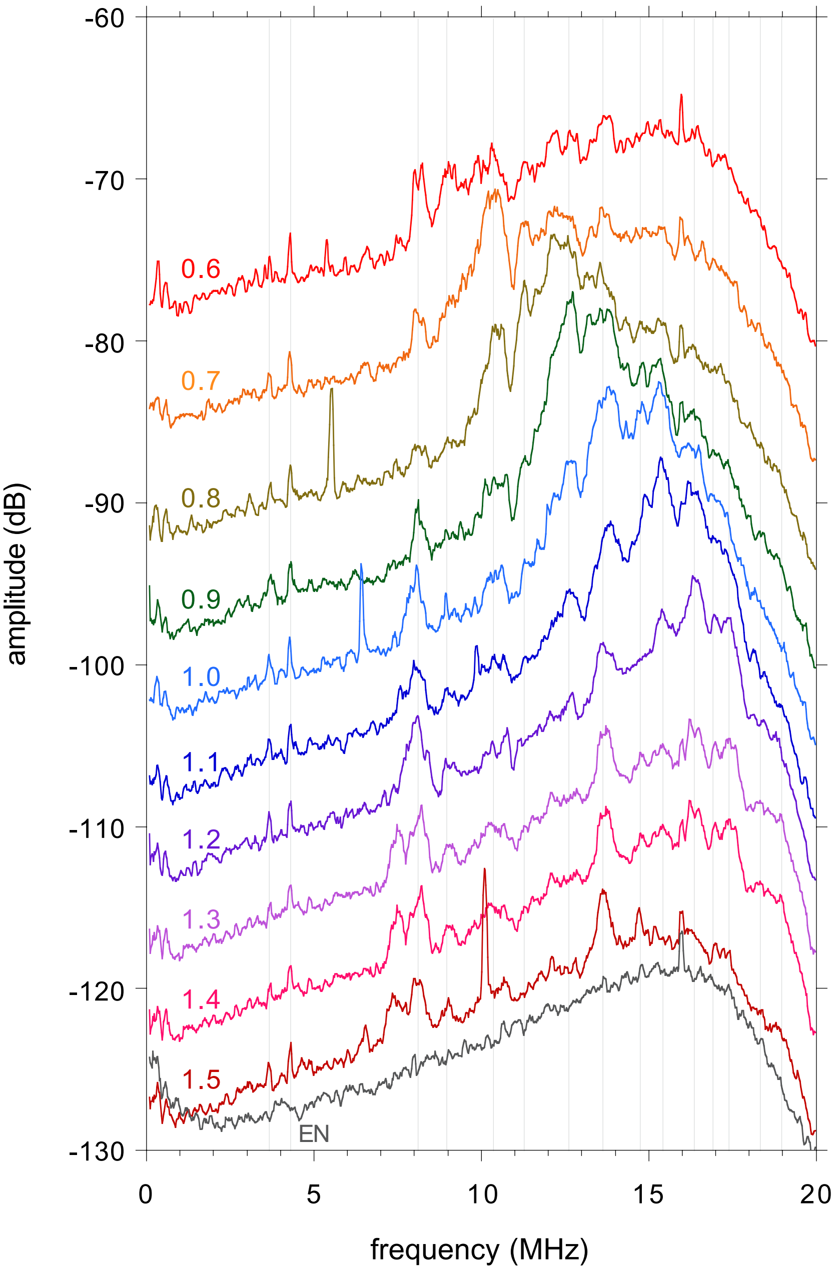

Fig. 8 Blank-tape noise spectra for head-tape speeds from 0.6× *to* 1.5× *nominal speed* (6.01 ms^{-1}). *The curves are offset for clarity, and labelled with the head-tape speed. Drive L509834, cassette 125M92N8M1, 40% RH, 22°C*

excitation frequency causes the position of the largest peak to jump from one pre-existing modal frequency to another. This line is quite linear, and can be extrapolated to intercept the frequency axis close to the origin. This suggests that the excitation has a characteristic wavelength (λ), given by

$$\lambda = \frac{\phi\,\pi\,RPM_{\mathrm{nom}}}{60\,gradient} \tag{1}$$

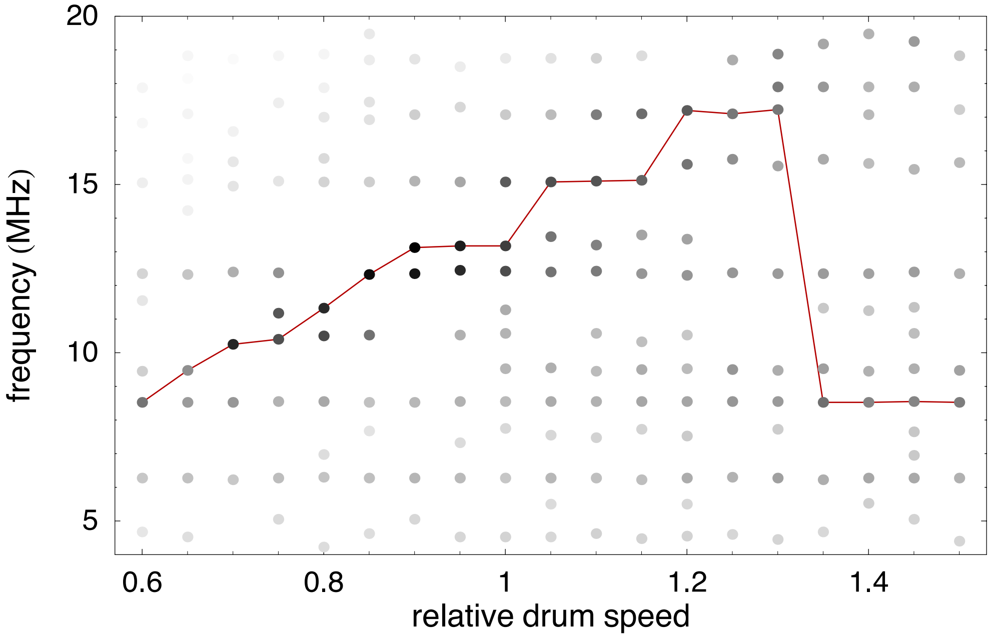

Fig. 9 Illustrating the change in position and size of peaks in a rubbing noise spectrum as the head-tape speed is changed. Points identify the position of peaks, the greylevel shows the size of the peak (darker = larger), and the red line shows the position of the largest peak. The linear region (0.6-1.3×) corresponds to a wavelength of 433 ± 4 nm

where ϕ is the diameter of the drum (30 mm), and RPM_{nom} is the nominal drum speed (3826.5 RPM). Fitting a straight line ($y = m\,x$) to this data gives a gradient of 13.87 ± 0.14 MHz, and hence a wavelength of 433 ± 4 nm[†].

The wavelength calculated from the observed speed dependence is a very reproducible characteristic of a head. For a chosen head, the same wavelength was obtained using either of the two methods described above. Moreover, in one experiment using method 1, ten different drifting speeds from 0.6× to 1.4× gave wavelengths that were consistent (at a high level of confidence, $\chi^2 = 10.1$, degrees of freedom = 9) with a single value of 467 ± 4 nm. This indicates that the characteristic wavelength of a head is independent of the drum speed, and hence head-tape speed.

Figures 8 and 9 show a very clear linear dependence on drum speed, which was a repeatable characteristic of this drive when in the drifted state. Other drives, however,

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[†] This error estimate is based on adjusting the chi-squared value to equal the number of degrees of freedom.

showed a much weaker dependence on drum speed, and a linear region could not be clearly discerned even when they had just undergone considerable error rate drift.

Detailed AFM Measurements

An Atomic Force Microscope was used to examine the ferrite read heads of DDS-3 tape drives in each of the following conditions:

1. Immediately after the error rate had been reduced by pulling new tape for five minutes (as in figure 2)
2. When the drive was in a drifted state (due to increased rubbing noise) after reusing a section of tape 200 times.
3. After a section of tape had been used many times (~1000) and the error rate had substantially recovered.

After pulling unused tape over the heads, the only features present on the ferrite were the many, relatively deep scratches due to abrasive ploughing by hard particles in the tape coating.

In the drifted state the surface of the ferrite also appeared featureless (figure 4) until it

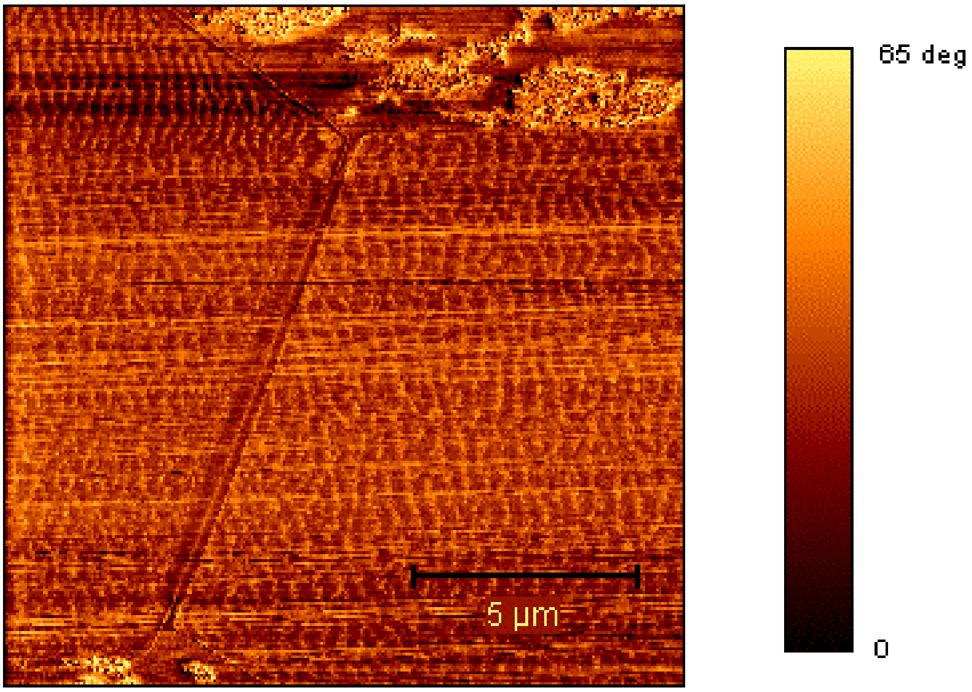

Fig. 10 Phase image of the same head shown in figure 4. Note that the “ripples” are more closely spaced in the top-left corner. The direction of tape movement is indicated by the approximately horizontal scratches on the surface of the head. Tape makes contact with the entire region shown in this image.

was examined in more detail. This revealed a subtle “ripple” pattern in both the topography and phase images. Ripples were only ever seen in the head-tape contact region on the ferrite - never on the glass. They had a height range of less than 3 nm and an RMS roughness of 0.4 nm. Analysis of the ripples using 2-D Fourier transforms showed that they were always aligned at ±10° normal to the direction of tape movement, and always had a wavelength that closely matched that calculated from the speed dependence of the head’s rubbing noise. As an example, the ripples shown in figure 10 have a wavelength of 426 ± 80 nm, whilst the speed dependence yielded a wavelength of 422 ± 4 nm. The actual wavelength (both of the ripples and derived from the speed dependence) appeared to be a characteristic of individual heads, since the two read heads on one drum could have significantly different wavelengths. In addition, the spacing of the ripples could sometimes be different on some parts of the head, as shown in figure 10.

The clarity of the ripple features appears to be linked with the clarity of the linear region in the speed dependence measurements (figure 9). With some drives, even when they had just undergone considerable error rate drift, ripples were difficult to see in the AFM images, and the position of the highest peak in their rubbing noise spectrum showed only a weak dependence on drum speed, with no clearly discernible linear region.

Ripples could also seen on the ferrite by using an optical microscope with differential interference contrast (DIC) filters.

Other authors have reported seeing ripples on magnetic recording heads when used with MP tape[6,7], but the mechanism by which these were formed was not explained.

An AFM was also used to examine the heads in a drive that had used tape many times, and whose error rate had substantially recovered. Unfortunately the results have been inconclusive. We currently believe that the ripples are less clear than in the drifted state, but that they are still present.

Discussion

The underlying impairment that causes the error rate to increase is clearly rubbing noise, caused by friction between the tape and the head. This has been directly measured, and explains the sensitivity of this phenomenon to factors that affect interaction between the tape and the head, such as the tape tension.

The speed dependence of the rubbing noise spectrum can be attributed to the ripples that form on the surface of the read head. As asperities in the tape move over the head they will interact with successive ripples with a period determined by the head-tape speed and the ripple spacing (i.e., wavelength). Frictional stress between the tape and head will, therefore, be periodic, and a large rubbing noise signal will be generated when this excitation frequency coincides with modal frequencies in the head. Well defined ripples on the head will result in a clearly defined linear dependence of the rubbing noise spectrum on the head-tape speed, but this behaviour will be less clear with weaker ripples.

In the absence of ripples, stress between the tape and the head will be random and continuous, so resonant modes in the head will not be excited, and the overall level of rubbing noise may be lower. However, error rate drift still takes place, so the ripples exacerbate the problem but do not cause it.

The nature of the ripples, and the origin of their characteristic wavelength, is still not clear. Is the wavelength an intrinsic property of the head's material (e.g., a periodic variation in composition or defect density), or is it an imposed feature, created by a mechanism that is external to the head (e.g., due to a mechanical resonance in the tape path). Several observations lead us to prefer the former explanation. Firstly, an external mechanism would have to scale linearly with the drum speed in order to make the resulting ripples be speed-invariant. Secondly, to explain the observation of varying ripple spacing over the surface of one head, an external mechanism would have to affect different parts of a head in different ways. Similarly, the external mechanism would have to affect a drum in a way that could lead to different wavelengths on its two read heads. Clearly, more work needs to be done to properly identify the ripples, the mechanism by which they form, and the way in which they interact with the tape.

An interesting question that remains to be answered, is "what is the systematic change that makes the rubbing noise worse as the tape is reused?" One hypothesis, suggested by the published work of Kawamata *et al*[5], was simply that the reduced abrasivity of used tape increases the level of rubbing noise. However, this explanation is based on a change only to the tape, so is unable to account for the *gradual* reduction in error rate (and rubbing noise metric) that occurs when unused tape is pulled across the heads. This latter observation suggests strongly that when the tape is reused, the systematic change that takes place occurs to the head, not the tape. In addition, a simple reduction in abrasivity is unable to explain the gradual self-recovery that takes place when the tape is used many times.

We do know that the rubbing noise will only increase if stress to the head is increased. This statement is probably a key to explaining the observed behaviour. Reusing the tape must change the head in a way that initially increases the stress, resulting in an increased error rate. If the tape continues to be reused then a very gradual reduction occurs in the rubbing noise, so the stress must be slowly reducing; however, it is not clear whether this change is associated with the head or the tape. Pulling unused tape across the head gradually changes the head in a way that reduces the stress.

One possible explanation for the change that takes place is that as the tape is reused and its abrasivity and roughness are reduced[1], the wear mechanism at the head-tape interface changes. Initially, abrasive ploughing by large particles of head cleaning agent (HCA) in the new unused tape creates a scratched, rough surface on the head. The rough tape and the rough head have a low area of contact, so interaction stresses are small, and the rubbing noise and error rate are low. As the tape is reused, larger asperities will be removed or deformed so that the tape surface becomes smoother. The aggressive ploughing is replaced by a gentler polishing action, and the head surface also becomes smoother. The area of contact between the tape and the head will increase, increasing the tangential friction stress and hence the rubbing noise and error rate. In this regime of gentle wear the ripple features may form, exacerbating the rubbing noise, as described above. We currently do not have a convincing hypothesis for the final change that takes place, causing the gradual self-recovery in rubbing noise and error rate. It may be related to a further reduction in roughness and abrasivity of the tape, or possibly to a change in the conditions of lubrication at the head tape interface.

Conclusion

Some combinations of DDS-3 tape drive and cassette experienced a rapid increase in error rate, followed by a gradual spontaneous recovery, when a section of tape was repeatedly used. The increased error rate was shown to be caused by an increase in rubbing noise, resulting from changes to the surface of the read head as the tape became smoother and less abrasive. Peaks in the rubbing noise spectrum occur at fixed frequencies that do not change as the tape is reused, or as the head-tape speed is increased. This suggests that the peaks are associated with standing-wave vibrations that are set up in the ferrite read head. In some cases, periodic ripple features that form on the surface of the read head excite these vibrational modes. The exact nature of these ripples, and the mechanism that causes the self-recovery are still unknown.

Acknowledgements

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Appendix A: Error Rate Drift with Increased Tape Tension

At an early stage in our investigation we observed that lowering the tension of the tape could reduce error rate drift. This suggested that the drifting process could be ‘accelerated’ (both speeded-up and enlarged) by raising the tension. Indeed, with the tension set to 1.7× the nominal value, drift of up to 200× could occur in only 40 passes.

Unfortunately, after considerable work had been completed, we realised that the increased tension had created a completely different form of error rate drift! Attempts to speed-up our work by using raised tension had sidetracked the investigation for many weeks, and ultimately delayed the work.

As the tape tension is increased there is a gradual transition to dominance by this second, unrelated type of drift. The impairment associated with the high-tension drift is a physical damage to the tape that has a similar affect on both the reading and the writing processes. Recovery to the error rate occurs immediately the heads move onto unused tape. The damage is localised on the tape, and occurs to a greater extent near the top of the track. This suggests it may be caused by contact between the drum and the tape.

Attempts that were made to measure the effect of relative humidity on the drift were done with the tape under high tension, so were dominated by the tape-damage drift. Due to lack of time the humidity dependence experiment was not repeated at the nominal tape tension.