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Articles:

The Dynamics of Surface Curvature and the Head-to-Disk Interface

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Track and bit densities continue to increase to meet the demand for storage capacity in the smallest possible space. A major factor contributing to that gain is made with lower fly heights. As the flatness, waviness and roughness features on the disk surface have decreased to accommodate the lower head clearances, the dynamics of the materials have not significantly changed. These dynamics are now such a substantial portion of the disk surface morphology that they could be the next practical barrier to increasing storage capacity.

In the disk and drive community there is a much used adage that says “there is no tradeoff for flying height.” The magnetic flux density in an air gap changes by the cube of the distance. Unfortunately, fly height modulation during the write cycle can cause the decreased flux density to be insufficient to saturate the media. Adding to this, fly height modulation during the read cycle can further decrease flux density to the point that data cannot be read.

The demand for increased areal density and ever larger storage capacities necessitates a lower flying height. Lower clearances equate to higher track densities and higher bit rates. Historically the task of delivering larger storage capacities has been divided into the four basic drive components, heads, disks, spindle and electronics and each, in turn, has been called upon to provide their expertise to these improvements. This has required the ability to recognize, identify and quantify the important parameters.

This paper discusses some of the disk surface morphology problems that affect the head-to-disk interface. The importance of disk dynamics has increased to the point that they are playing an ever more significant role. In reality, the dynamics have not changed over the past thirty years. What has changed however, is that flying heights have decreased from 200µ” to 0.15µ”, head loading has decreased from 350g to 2g, disk diameters have decreased from 14” to <1”. All these factors contribute to the fact that disk characteristics such as disk dynamics and surface morphology that were never a problem 30 years or even 5 years ago now have considerable importance.

One of the last major “performance driven” mechanical improvements was the disk drive spindle. It is easy, post-facto, to examine why, even from this very short historical perspective. Recognize, identify and quantify: Recognize the need to increase track density, identify the ball bearing spindle runout as a major limiting factor and, quantify the runout by track position error and spindle testing. All of which pointed to the need for, and development of, a better rotation mechanism, viz: fluid bearing spindles. Three years of difficult development reduced to a single paragraph.

Most companies are starting to recognize the need for a new performance driven mechanical improvement. This time, the head-to-disk interface improvement embraces the axial direction rather than the radial direction normally associated with improved track densities. Recognize, identify and quantify. The recognition is being driven by problems with both data and servo integrity in the form of TMR (track misregistration) and PES (Position Error Signal). With higher rotation speeds, lighter gram loads, very low fly heights, and extreme flux density deterioration in an air gap, any fly height modulation has become critical[1]. Specific surface morphologies have been identified as forcing functions and a lot of attention has been directed at waviness, micro and nano-waviness and now, surface flatness and “macro-waviness,” wavelengths above 2mm.

The quantification of surface flatness and its effect on the head-to-disk performance has driven improved measurement capabilities over the last ten to fifteen years. These capabilities were developed to replace the limited resolution of capacitance and eddy current probes when measuring runout, velocity and, most importantly, acceleration, the rate of change of the vertical motion between the disk and the head and the driving force of fly height modulation. The new measurement is often called “surface curvature.” When it is measured along the data track it is referred to as “circumferential curvature” or “tangential curvature” and when measured across the data tracks it is referred to as “radial curvature.” The measurement is typically made with a flatness measuring device that can trace its origins back to “drag-stylus” technology.

The “drag-stylus” was initially applied to measuring “ski-jump” and “dub-off” conditions at the inner edge where clamping forces were applied and the outer edge to extend the usable surface to the maximum possible radius. Current measurements are made by several differing techniques usually involving laser interferometers scanning across the surface while the disk is held in a fixture.

These instruments can reveal much of the surface morphology but care must be taken to insure that sufficient detail is captured relating to the head to disk interface. Figures 1 and 2 demonstrate this requirement. In Figure 1 we have a scan of a single radius showing the general shape of the surface with a “best plane fit” algorithm applied. The total runout is 2.25 microns but with a smaller superimposed macro-waviness (2 to 5mm wavelength) of about 50 Angstroms. Figure 2 shows a small section of Figure 1 showing the outline of a head slider for a clearer understanding of the surface morphology and the head-to-disk relationship. The head representation is to scale for a 5nm fly height.

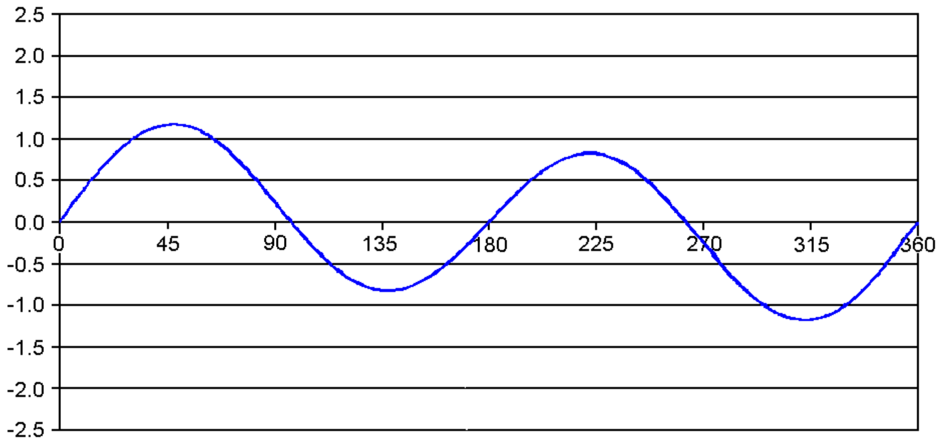

Figure 1 of track static runout

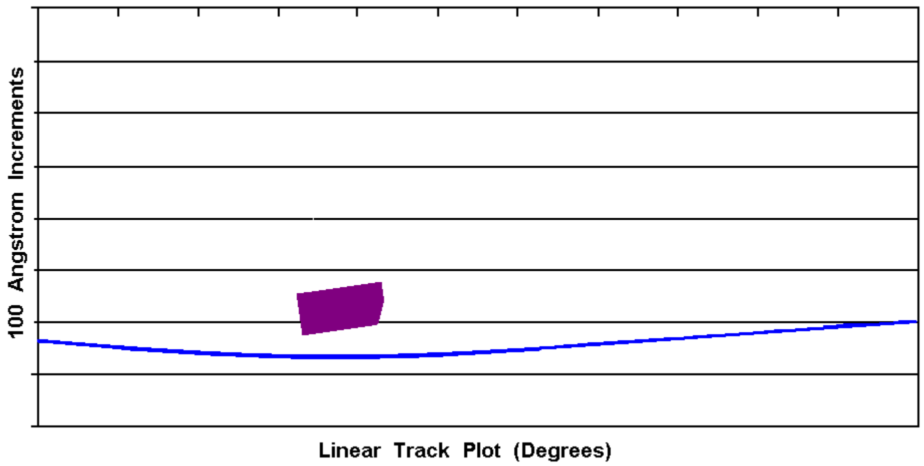

Figure 2: Head on static track with runout and macro-waviness.

Instruments such as the Optiflat, (Zygo Corp.) and the Mesa (Veeco Corp.) typically have sufficient resolution to detect these macro (long wavelength) features. While the lateral resolution (X, Y) is sufficient, the vertical (Z) resolution measurement capability, repeatability and uncertainty need to be greatly improved. Improved measurement tools are required for the very low values that are needed today; 10µm runout is no longer considered acceptable and heads no longer fly at several micro-inches. Head fly heights are now below the minimum resolution of some of these tools.

As the fly heights decrease and the head size drops, polish features with shorter wavelengths become more critical and are a much larger portion of the fly height budget. With head slider lengths »600 microns, wavelengths shorter than 2 mm need to be considered in the fly height modulation model. Lateral accuracy must also be improved to be able to make the “curvature” measurements required. Full surface instruments lack the lateral resolution to detect the very short wavelengths (waviness, micro-waviness, nano-waviness or roughness) and the vertical resolution is insufficient for the newer requirements. But, there is a far more serious deficiency.

The calculation that is used for the curvature is designed to show up areas of the disk surface that the head cannot negotiate without excessive fly height modulation being induced. Somewhere between the extremes of a perfectly vertical and a perfectly flat surface is an acceptable rate of change in the surface runout that does not have an adverse effect on the fly height modulation. The allowable curvature will be based on several factors including the design fly height, reaction of the head structure to air bearing pressure variations and the disk design spin speed.

All these factors can be added to the curvature calculation and limits can be established for the various applications provided we can resolve the vertical and lateral measurement resolution problems. Since scatterometry is a comparison technique with questionable accuracy[2], the logical replacement for the range-finding or fringe interference measurement technique would be a Doppler technique with a proven resolution down to 0.01Angstrom[3]. Furthermore, increasing the data gathered beyond the typical 512 X 512 square used by the Optiflat or Mesa type instrument would increase the effective “bandwidth” and would increase the ability to capture other features that could affect the fly height modulation, i.e. the waviness, micro-waviness, roughness, etc. (See Figure 6.)

Ideally, a single instrument should be used to capture all features from micro-roughness to flatness. Unfortunately, the data acquisition speeds and storage capacities would be well beyond reasonable limits and, even with all of those capabilities there is *still* a glaring deficiency that is yet to be addressed. The reason that this paper is titled “The Dynamics ....” is because disk drives are dynamic devices. And, there are a few laws of physics that apply.

1. There is no such thing as a perfectly balanced mass.

2. There is no such thing as absolute smooth rotation.

3. Disks resonate and flutter. An 84 mm disk resonates at approximately 750 Hz.

4. When excited in the drive, by imbalance, spindle, air flow or shock, it will induce 8.33 cycles of oscillation (at 5400 rpm) onto the disk surface with every rotation.

It is interesting to note that all current materials, aluminum, ceramic or glass, resonate at approximately 700 to 800 Hz. The advantages and disadvantages of the various materials do not affect the basis of this discussion. Likewise, the relative advantages of thicker materials and lower resonance amplitude are quickly negated by the demands for an ever lower fly height.

As the head flies over the surface and is forced upward by the disk, energy is dissipated to some degree by the air bearing but the remaining energy is absorbed by the head spring support mechanism. If the upward slope is of sufficient duration (once around runout at a sufficiently slow rotation rate), the natural frequency of the head mechanism compensates and the fly height stability is only compromised by the slight air bearing compression. However, for macro-waviness (2 to 5 mm wavelength) and even for wavelengths as long as 40 mm, the frequency is much higher than the fundamental frequency of the head suspension. In this case, the energy of the "disk push" is stored in the suspension and as the disk surface starts to drop away, the energy is released, but not quickly enough to follow the disk and so the fly height modulation is increased.

Figures 3 shows the effect of 1µm (not an unusual number) of flutter imposed on the 2.5µm runout measurement from Figure 1. Figure 4 compares with Figure 2 and shows the relative spacing of the head over the disk in a dynamic situation involving flatness, flutter and macro-waviness. Obviously, the short wavelength dynamics have a much greater impact than the overall flatness and serve to increase the severity of the local "slope." Figure 5 shows an area of the track comparing static flatness to dynamic flatness. It now becomes immediately obvious that static state curvature measurements can be very misleading.

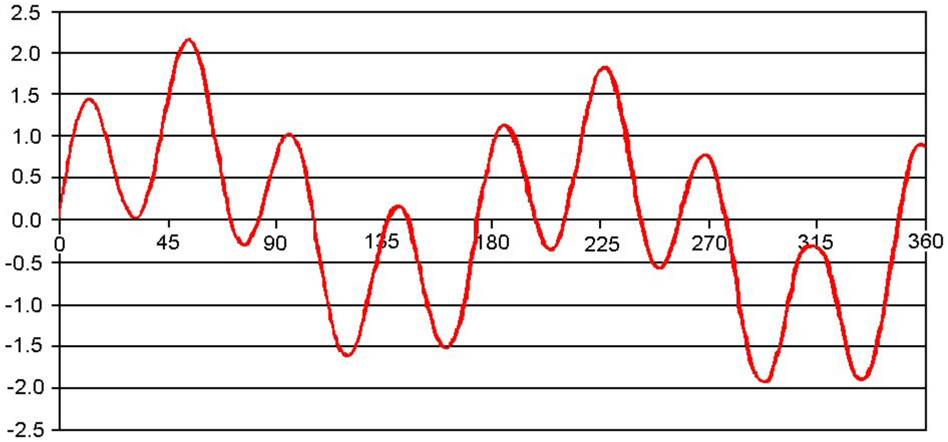

Figure 3: Linear plot of dynamic track runout including flutter

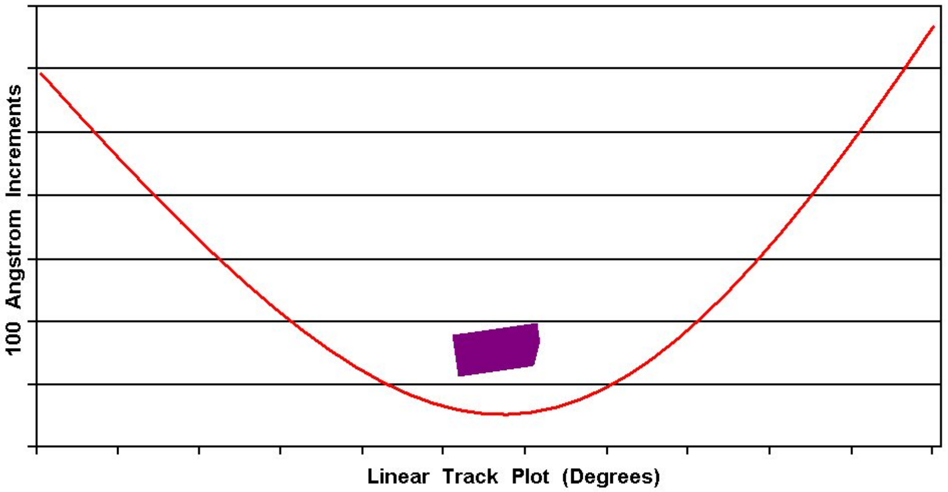

Figure 4: Head on dynamic track with runout, macro-waviness and flutter

Another interesting note, there is an apparent lack of "dynamic" flutter at the higher multiples of the resonant frequency. For example, the scarcity of flutter at the eighth octave (96 kHz) with a wavelength, at a 30 mm radius, of approximately 200 microns (micro-waviness). The instrumentation used for this study is capable of measurements and repeatability into the range of 0.02 Angstroms and the calculated eighth octave amplitude of a one micron flutter should be in the range of 75 Angstroms. The logical conclusion is that we are dealing with a homogenous material generating a relatively pure tone with few overtones or the hoop stress dynamics need to be examined[4].

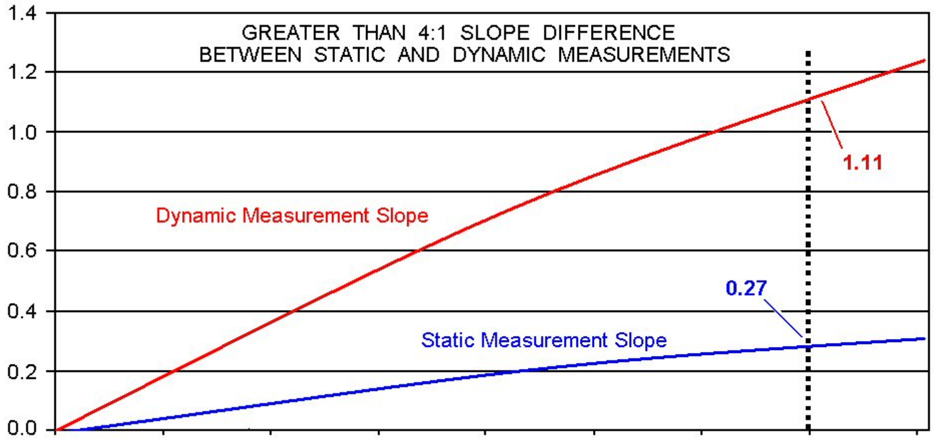

Figure 5: Slope difference between static and dynamic runout

In an interesting experiment to confirm the “fly away” problem, a disk tester from Guzik Technical Instruments was modified to accept two Doppler laser measurement beams, one focused on the head and the second focused at the disk immediately adjacent to the head. The fly height modulation was calculated as the differential between the two laser measurement channels and the surface morphology information was captured from the laser focussed onto the disk. A 2F signal was written using the Guzik electronics. Any effects from fly height modulation on that one write revolution were written onto the disk. Several hundred read cycles were then executed, the amplitudes were sampled several thousand times per revolution and the results were averaged on a point by point basis. This averaging yields a stable representation of the average track amplitude.

Then, a single read cycle was measured and compared to the average. Simultaneously, the LDV signals were recorded. The difference between the mean average read signal and the single read cycle provided the non-repeatable or signal amplitude modulation information. This information was compared to the fly height modulation information and to the surface morphology information and confirmed the “fly-away” signal loss problem. Other work of this same nature has been performed at Hewlett Packard and Quantum Corporation (now Maxtor) and published in I.E.E.E. proceedings[5,6].

While there are many factors that affect the head fly height, fly height modulation in very low fly applications can be dramatic. The amazing thing about the disk drive in Figure 6 is channel electronics and error correction codes that allow this drive to function to the high degree of performance common in todays products.

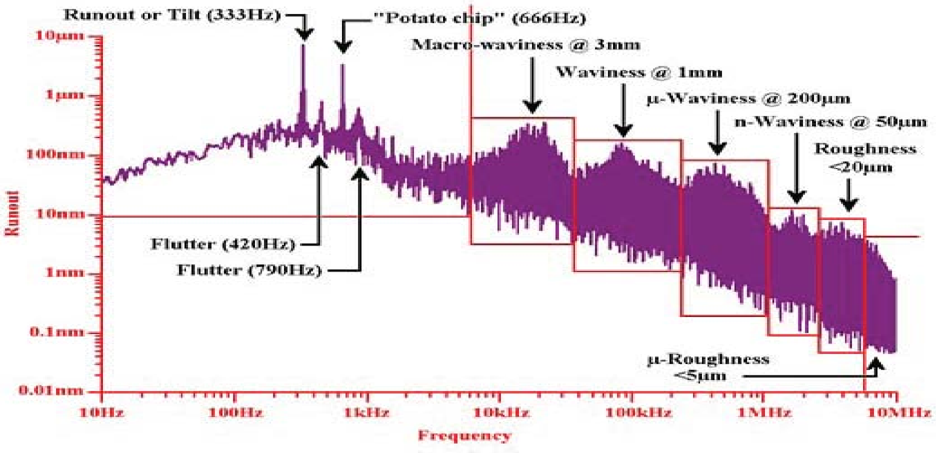

Figure 6: Disk flutter and fly height modulation

All of the above addresses the dynamics of curvature in the circumferential direction. What about the corresponding radial curvature, the ski-jump and dub-off portion of the curvature measurement? Let's look at several factors very quickly. First, the seek motion introduces more twist (sway mode) to the suspension than any extremes of reasonable edge condition of the disk. Second, the head can easily adapt to a high degree of surface radial curvature (as long as there is low circumferential variation). Third, we are considering the ability to move over the surface, not to write and read data; that function is performed while the head is on-track, not during track seeks. If the ID to OD head seek time equals the rotation time, there is almost a ten to one difference in the circumferential to radial disk surface speed under the head. Within reasonable limits, radial curvature has minimal impact compared to the effects of dynamic circumferential curvature.

Conclusion:

The surface morphology has improved to the point that disk dynamics have become the dominating feature. The potential to develop a substrate that does not flutter is likely to be expensive and time consuming. The head design to eliminate the fly height modulation and meet all of the disk size and rotation speed requirements is going to be monumental task. Is it possible that the solution may require the long talked of surface contact head?

In either case, dynamic measurement with extremely high resolution (sub-Angstrom) capabilities will be required to develop the technologies to meet future disk drive component design requirements.

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[1] "The Effects of Disk Morphology on Flying Height Modulation: Experiment and Simulation," Brian H. Thornton, D.B. Bogy and C.S. Bhatia, Computer Mechanics Laboratory, University of California, Department of Mechanical Engineering, Berkeley, CA.

[2] "Scattered Thoughts," Steven Miller, Breault Research Organization, OE Magazine (The Monthly Publication of SPIE, The International Society for Optical Engineering,) January 2004.

[3] The 1999 Nobel Prize in Chemistry, the Royal Swedish Academy of Sciences awarded to Professor Ahmed H. Zewail, California Institute of Technology, Pasadena, California, U.S.A.

[4] "Resonant and Stationary Waves in Rotating Disks," Dr. Albert C. J. Luo, Professor of Mechanical Engineering, Southern Illinois University at Edwardsville.

[5] "The Effect of Disk Platter Resonances on Track Misregistration in 3.5 Inch Disk Drives," Jeffery McAllister, Hewlett Packard Company, IEEE Transactions on Magnetics, Volume 32, No. 3, May 1996

[6] "Predicting Track Misregistration (TMR) From Disk Vibration of Alternate Substrate Materials," Padmanabhan Srikrishna and Kumar Kasetty, Quantum Corporation, IEEE Transactions on Magnetics, Volume 36, No. 1, January 2000.

About the Authors:

Jim Eckerman

Jim Eckerman is co-founder and President of THoT Technologies with over 35 years of experience in the disk and drive industry starting with Caelus Memories in 1969. He has held various technical positions at Singer Research, Univac, Memorex and Xerox. He joined start-up Caere Corporation which developed pattern recognition for print and returned to the data storage industry to work at MTS and ProQuip, the forerunners to Phase Metrics before founding Lotus Technologies in 1987 and THoT in 1991. BA, Mathematics, Univ. of Maryland, Zama, Japan, 1967.

James Chao, Ph.D.

Dr. James Chao is currently an Executive Director in Research & Development of Komag, Inc. which manufactures magnetic recording thin film media. Dr. Chao has his Ph.D degree from University of Kentucky in 1979 from Material Sciences. He joined Control Data Corporation (Seagate now) in 1981 after two years work as a post-doctoral research associate. In 1986, he joined Digital Equipment Corporation and, in 1991, moved to HMT Technology. In 2000, HMT Technology merged with Komag, Inc.

Dr. Chao's 20 years of industrial experience are concentrated in magnetic recording media R&D, engineering & production, especially in the tribology/reliability area of head and media. Currently, he second-line manages four key process areas in Komag including: texture, wash, lube and post-lube. He has seven industrial patents and more than 50 technical publications.

Review of the IDEMA Perpendicular Recording Symposium (2004)

by Tom Coughlin, Coughlin Associates

Introduction

Perpendicular recording, sometimes also known as vertical recording, is a technology for storing magnetic bits of information with the direction of magnetization normal to the disk surface rather than along the disk surface as in conventional longitudinal recording. Work on perpendicular magnetic recording for digital magnetic recording has occurred in the US and elsewhere for many years. It has taken a long time for perpendicular magnetic recording to show an advantage over longitudinal magnetic recording although theory indicates that perpendicular magnetic recording should be more stable than longitudinal magnetic recording for high enough recording density. For the first time in 2003 perpendicular magnetic recording areal density demonstrations have shown higher areal density than longitudinal magnetic recording areal density demonstrations. It now appears that perpendicular magnetic recording will achieve commercial success within the next few years as demand for higher capacity disks brings the disk drive industry into the areal densities where perpendicular magnetic recording will be required. IDEMA held a perpendicular magnetic recording symposium on February 26, 2004. The symposium focused on the history and theory of perpendicular recording, key component characteristics for perpendicular recording, component integration issues and industry timing and costs. This paper offers a review of those presentations.

Theory and Mechanisms

Mason Williams from Hitachi GST and Dr. Neal H. Bertram, Professor at UCSD/CMRR, gave presentations on the history and theory of perpendicular magnetic recording. Mason defined perpendicular recording as recording where the predominant direction of the recorded magnetization in the magnetic medium (disk) is perpendicular to the plane of the medium. Most modern designs for perpendicular magnetic recording involve a soft magnetic layer in the medium below the perpendicular recording layer that increases the efficiency of the write field and provides greater perpendicular field orientation during writing.

In 1898 V. Poulsen demonstrated analog (audio) magnetic recording of a steel wire. He initially thought that he was magnetizing the wire in the direction normal to the wire length but eventually found that in fact the recording was being done along the direction of the wire. In 1958 A. Hoagland published a shielded pole head design at IBM. IBM had planned to have the magnetic disk product that followed the Ramac use perpendicular magnetic recording but had to go back to longitudinal recording due to media defect problems. In 1977 S. Iwasaki introduced CoCr perpendicular recording on a tape with a simple pole and auxiliary pole recording head. In 2000 H. Takano of Hitachi reported over 50 Gb per square inch (Gbpsi). In 2003 Seagate demonstrated up to 170 Gbpsi using perpendicular recording.

Williams believes that perpendicular recording hasn't shown an advantage over longitudinal recording in the past since a) areal density was primarily limited by resolution (flying height and head dimensions), b) with longitudinal recording increasing at >60 % per year areal density growth it was difficult for perpendicular to keep up and show an advantage, and c) the additional complexity of perpendicular recording discouraged people working with it.

Thermal stability issues with longitudinal recording are making it difficult to increase areal density with the conventional recording mode. This has prevented the usual continual scaling down of the thickness of the medium, the gap length, track widths and flying height. The flying heights are now so low that it is difficult to get additional areal density increase with lower flying height (the areal density increases inversely with the square of the flying height). This has resulted in renewed interest in perpendicular magnetic recording. Also read heads with perpendicular recording provide a narrower read profile than with longitudinal recording.

Perpendicular recording limits appear to be higher than longitudinal limits. INSIC work indicates that 700 Gbpsi is possible and it may be possible to exceed 1 Tb per square inch with perpendicular recording alone. Note that for a perpendicular system to show superiority to a longitudinal recording system it must be optimized.

Shielded heads can offer some significant advantage in the resolution of the head write field but do so at the cost of much lower field strength. With the proper trade-offs in design it may be possible to use trailing shielded heads such as those proposed by M. Mallary and much earlier by A. Hoagland to achieve higher linear recording densities. Uniformity of media parameters is key to obtaining the required optimization in order to achieve high perpendicular recording areal density.

Neil Bertram, professor at University of California, San Diego, discussed the theory of perpendicular magnetic recording. Dr. Bertram showed that 200 Gb/square inch is achievable with a small enough transition parameter. One approach to increase the recording density is to use shielded perpendicular recording heads to increase the effectiveness of the recording field. If the magnetization of the perpendicular media is at an angle the effective switching field for reversing the media magnetization can be significantly reduced. For a 45 degree magnetization the switching field is half the anisotropy field of the media. Tilted magnetization also helps with reducing track edge writing. To achieve high perpendicular recording densities the transition parameter much be reduced and the anisotropy field must be increased as much as possible and the switching field made as low as possible.

PERPENDICULAR MEDIA TECHNOLOGY

Gerardo Bertero of Komag presented a case for granular perpendicular magnetic media. By sputtering at lower temperatures with the proper media alloy, isolated grains with perpendicular magnetic recording are formed, thus we end up with granular perpendicular magnetic media. The grains are isolated away from the base of the media, while they may be close enough to cause exchange coupling between the grains at the base of the media grains. A ruthenium layer lies below the granular perpendicular magnetic media. A seed layer in addition to the ruthenium layer lies between the magnetic recording media layer and the soft magnetic layer. A very thin ruthenium layer can be used between two or more soft magnetic layers to create antiferrimagentic coupling between the soft magnetic layers, similar to that used in synthetic anitiferrimagnetic media. The antiferrimagnetic coupling of two soft magnetic layers reduces the formation of magnetic domains in the soft magnetic layer. With enough soft layers with antiferrimagnetic coupling, the soft magnetic domains can be effectively eliminated. Use of granular media and antiferrimagnetic coupled soft layers allows significant increases in media signal to noise vs. non-granular perpendicular recording media.

Bertero then showed data that a 2 dB signal to noise improvement can be obtained for a shielded pole perpendicular write head vs. an unshielded write head. He reported that a 1000 kbpi linear recording density can be achieved with about $10^{-4.5}$ bit error rate. In conclusion he stated that perpendicular recording media is on par with longitudinal magnetic recording media although additional work is needed to reduce exchange coupling between the media grains, minimize the spacing between the SUL and recording layers, reduce soft layer domain formation, and minimize bit curvature.

Noel Abarra from MMC spoke on technical and manufacturing challenges for perpendicular recording media. Perpendicular recording is said to be necessary to achieve continual areal density growth. He showed a road map for magnetic recording technology indicating that longitudinal recording may continue until 2007 with the first perpendicular recording products appearing in 2004. Heat assisted magnetic recording (HAMR) technology is projected to be needed about 2009 to keep areal densities increasing with discrete bit recording technology coming into play about 2011. MMC believes that the initial generations of perpendicular magnetic recording can be accomplished with conventional media sputtering systems (with up to 12 process stations). Eventually more than 12 process stations will be required to continue the increase of perpendicular recording density. MMC also feels that granular perpendicular recording media may be the most promising approach. They showed that as inter-granular coupling decreases the magnetic hysteresis loop slope decreases and magnetic coercivity increases. By creating antiferrimagnetic coupled soft magnetic layers off-track erasure in perpendicular magnetic recording media can be reduced to acceptable levels.

Optimization of perpendicular recording media also involves shielded write heads and improvements in the uniformity of magnetic media properties by optimizing the deposition properties and gas distribution. Surface roughness was also reported to be an issue requiring media optimization to resolve with perpendicular recording media. In conclusion, MMC reported that similar throughput was achieved with perpendicular magnetic recording media vs. longitudinal recording media. Incrementally higher costs for PMR media vs. LMR media can be expected due to additional SUL layer and lower uptime of the sputtering systems. Minimizing SUL thickness and number of media layers will enable use of existing sputtering equipment.

Hiroyuki Uwazumi from Fuji Electric described work they have done using electroless plated NiP as a soft under layer in perpendicular media. They took this approach because of concern with the additional sputtering time, maintenance costs, and capital purchase requirements that they perceived for sputtering thick, 100 nm thick, soft magnetic under layers. They decreased the concentration of phosphorus in electroless NiP to make the resulting layer magnetic (about 20% P is common in the non-magnetic NiP used for disk substrates). The issues for plated magnetic NiP are the magnetic properties, surface roughness, recording characteristics and spike noise. In the Fuji Electric experiments the magnetic NiP layer was plated over non-magnetic NiP on the Al substrate.

They were able to get 0.3 micron Ra on NiP soft under layers, almost the same roughness as for comparable non-magnetic NiP layers. They developed a “more precise polishing process" that gave a 0.10 nm Ra with a 1.5 micron thick magnetic NiP under layer. Note that to compensate for lower Bs (0.5 T) of NiP soft under layer it had to be much thicker than conventional sputtered soft under layers. For a 2.1 micron NiP soft under layer Hc = 15-20 Oersted, a bit greater than many sputtered soft under layers. There appeared to be no relationship between Hc of the perpendicular media layer vs. the NiP soft magnetic under layer thickness. The observed Hc was the same as for perpendicular media with 15 nm thick sputtered soft under layer. Fuji Electric found that a combination of 0.5 micron thick plated NiP magnetic soft under layer combined with a 25 nm thick sputtered CoZrNb film gave a good combination soft magnetic under layer with similar overwrite to sputtered only soft under layers media.

The head used for their recording tests had the following parameters: 0.3 micron write track width, Bs = 1.8 Tesla, 0.2 micron read track width, 80 nm shield gap length, and 12 nm flying height. They reported much lower spike noise (from magnetic domains) for NiP soft under layers 2.1 micron thick than for a 200 nm thick sputtered soft magnetic under layer. The NiP plated films have considerably greater noise in the low frequency region of the frequency spectrum (long wavelengths). This noise was said to be reduced by controlling the plating process, but is still somewhat higher than for sputtered soft magnetic under layers.

Robert Weiss from Intevac spoke about tools for media production. He stated that the next generation of sputtering tools (such as the Intevac Lean Machine) should allow sputtering media up to 1 Tbpsi. He advocated thinking of an integrated approach rather than a piecemeal media factory. However this approach must remain cost effective since there is no sign that the market supports technology-based pricing but there is also no sign of significant easing of the technology development pace. Perpendicular magnetic recording will not allow a price change but it threatens to increase the costs of making media.

Disks are pushing the limits of the film materials technology due to the number of layers and layer thicknesses. To save money media companies need to leverage the installed base with backwards compatibility. The requirements for new sputtering equipment are that it be expandable, flexible to support large numbers of stations and easy to reconfigure, give higher output at lower cost, accommodate smaller disk sizes, be reliable and available, leverage existing processes and incorporate new technologies (not too much to ask for!). He then went into some detail describing the Lean Sputtering Machine offered by Intevac and comparing it to the previous generation MDP-250B sputtering machines. Whereas the MDP-250B sputtering machine was limited to 12 process stations the MDP-200 Lean can easily handle at least 24 stations in a smaller overall floor space foot print.

In addition to new sputtering tools he also discussed additional process tool improvements needed such as in-situ cleaning, in-situ texturing, in-situ metrology of particles, and in-situ lubrication. In other words maximize the operations while the disk is under vacuum. Process station modules much be created that support soft under layer deposition, improve overall target utilization, allow multi-layer sources (rotating), allow improved hard overcoat deposition (cathodic arc carbon films), and allow vapor rather than dip lubrication. The soft under layer source much provide full surface even erosion allowing utilization of over 40% of the 6-9 mm thick targets. They must also allow removable carriers for minimal down-time during cleaning and service.

Intevac reported that they have achieved very high target utilization magnetron sputtering systems with a novel pole design for both non-magnetic and magnetic materials. They have developed a multi-source target with four magnetrons rotating for 2-4 layers or on-tool alloys. They have also developed a source for super lattice perpendicular media deposition. Protective overcoat films are expected to move from hydrogen and nitrogen carbon alloys to pure carbon. Such products are expected to be available within one year. They are also working on non-carbon alternatives for future product generations including reactive sputtered films such as SiN, including a new RF/DC source and ionized PVD. Vacuum vapor deposition has been a subject of research for many years. Intevac reports that their experimental vapor lube media have excellent corrosion performance, CSS equivalent to standard dip lube media, and tunable bonded thickness.

Perpendicular Head Technology

Moris Dovek from Headway stated that today's typical PRM head has a shielded pole with two layer coil. The shielded pole design shows significant improvement in BPI (bits per inch). For shielded pole one trades loss of gap field strength for sharper field gradients. This includes some longitudinal field that improves the overall switching field of the head. For these shielded pole designs the neck height is the most sensitive design parameter for the field strength.

Perpendicular recording shows much higher low frequency amplitude than comparable longitudinal recording although the amplitude rolls off faster for perpendicular compared to longitudinal recording according the modeling. Actual experimental perpendicular media roll off is better than shown in the model. Perpendicular recording allows much narrower write widths for a given pole width than is possible for longitudinal recording (a 0.03-0.04 micron advantage). Thus the off track recording characteristics for perpendicular recorded media are distinctly better. Otherwise perpendicular and longitudinal writers suffer similar limitations.

Currently perpendicular magnetic recording has been pushed experimentally to about 20% higher BPI than has been achieved with longitudinal recording. The track pitch and track density advantage of perpendicular recording is not as clear cut since the skew and pole bevel affect the track pitch. Thus the major practical advantage for perpendicular magnetic recording appears to be mostly in BPI. Thus the keys to higher areal density will be driven by media thickness and magnetic spacing. Perpendicular magnetic recording heads will probably require much tighter process tolerances. Because of the influence of the soft magnetic layer side fringing effects are often worse for perpendicular vs. longitudinal magnetic recording.

Dovek stated that the first generation perpendicular magnetic recording heads can use the existing production tools but this may not be true of future generation products.

Lamar Nix from Hitachi GST spoke on perpendicular heads for tomorrow's HDD. Nix showed that perpendicular media is easier to write and that the read sensitivity they could accomplish for the same reader width was considerably higher for perpendicular than for a longitudinal recording media. He said that perpendicular recording products will come into use sometime after 100 Gbpsi areal densities. He also spoke about the skew angle constraint on track widths and said that this could be solved by using a trapezoidal shaped pole. He also said that the perpendicular write field drops rapidly with shrinking pole width dimensions. Combined with skew angle compensation the thickness to width ratio for heads is limited to 2:1 or less. He also noted that fringing fields can be significant and described a write stability that becomes much worse with decreasing write track width for single magnetic layer write heads. This instability could be significantly reduced by using a laminated deposited pole. His data also seemed to suggest that this stability could be further improved with antiferrimagnetic coupled multi-layers in the main pole.

Trailing shields were also shown to improve the resolution of the writing. Addition of side shields offered significant benefit in increased track density. However with all this shielding the shunting of the magnetic flux makes it difficult to get sufficient write field for the media out of the head. In the area of head manufacturing processes, Nix discussed techniques using deep UV lithography to create precise head poles. The ability to control the width of the poles decreases as the length of the pole decreases and we get close to the flare point at the neck of the pole. It should be noted that the addition of trailing and side shields adds three extra critical dimensions to perpendicular head design offering additional challenges for both wafer and slider level processing.

Drive Integration of Perpendicular Recording Technology

Yan Wu from Maxtor described progress and challenges in perpendicular drive integration. He said that companies should be prepared to implement perpendicular recording in the event that longitudinal recording reaches its limits in areal density. Maxtor has started working with current longitudinal drives and substituting perpendicular recording components in order to find solutions to known issues as well as to uncover unknown issues. Their goal is to find out what needs to be changed and determine what trade-offs need to be made with limited resources they are seeking to change as little as possible in the drive platform.

In the perpendicular drive builds they had to add a differentiator to transform the step response waveform for isolated transitions in perpendicular recording to pulse response waveforms that current drive channels are built to work with. Some new default settings are needed with these standard channels to work with the resulting pulses. Standard servo patterns were used.

They found that several generations of channel chips used in longitudinal recording worked fine. In the future they plan to use channels optimized for perpendicular recording.

Yan Wu referred to a paper published eight years ago by Censtor Corporation on the major issues then seen in perpendicular recording: media relaxation (thermal decay, especially at low recording densities), head induced media erasure, resolution limitations due to head-to-underlayer spacing constraints, and extreme sensitivity to magnetic stray fields.

In contrast with these historical results Maxtor reported that perpendicular recording in their drives showed very low amplitude thermal decay (however it was not clear from the data that the erasure experiments were done at lower recording densities where perpendicular recording should be expected to show maximal thermal decay). Write erasure of prior data was observed and Maxtor feels this will be an issue if heads and media are not optimized—the effect is worse as written tracks get narrower. The perpendicular drives showed a couple of orders of magnitude worse error rate for a given frequency of external vertical (perpendicular) magnetic field and at half the applied field amplitude. In all they found that the perpendicular drives were 7 times more sensitive to external magnetic fields with vertical fields showing the greatest sensitivity. This is an issue that needs to be addressed for commercial drives.

Some additional challenges Maxtor identified are:

- Side writing occurs at high skew angles unless the write pole is properly shaped
- Side reading can occur through the read shield
- Wide write erasure (side erasure)
- Some issues with media performance uniformity both around the track and from ID to OD

In order to prevent side reading due to the read shield they suggest never leaving too bid a DC erased region on the disk, starting with an AC erased disk, and writing an AC pattern during servo writing.

Side erasure severity is sensitive to media coercivity, nucleation fields, media squareness, and soft under layer properties. Head design also has a major impact. Write preamps can be contributors due to the effects of write current boost and rise time. This could be an issue limiting the ultimate application of perpendicular recording unless it can be controlled.

Maxtor was able to build and test drives with dual layer perpendicular disks and heads. These drives were fully functional and could boot Windows operating systems and have also remained operational for more than two years.

Stray field sensitivity was a concern but not felt to be a limiting factor. Remaining major issues from Maxtor's viewpoint were optimization of head/media performance to get consistently high BPI and TPI by controlling the read and write wide issues and reducing stray field sensitivity. Work is also needed to qualify perpendicular-ready read channels.

Francis Liu from Western Digital spoke about advanced perpendicular recording head technologies. He predicted an areal density growth curve of 40-45% CAGR going forward. Liu showed a technology roadmap showing perpendicular recording will probably be used for 95-mm disk capacities greater than 160 GB (about 120 Gbpsi).

The heads used in the WD experiment had a six turn single layer coil, 15 micron yoke length, P3 saturation magnetization field of 2.35 Tesla and P2 saturation magnetization field of 1.6 Tesla with thickness of 1 micron. The head poles were trapezoidal, shield-to-shield spacing was 640 Angstrom. They were able to demonstrate ~146 Gbpsi recording with 15% off-track capability in 747 curves (5.3 micron track pitch, 189 kTPI). They observed no side writing at various skew angles. WD results show a 10% improvement in TPI vs. a comparable longitudinal recording.

Multiple write/read cycles showed no side erasure. WD work with a side-shielded perpendicular write pole design showed a 15% PW50 improvement for a shielded pole head with over 2 times greater write current required for an optimal write. Resolution improvements of about 18% were observed. In saturation OW appears to be about the same. NLTS was improved for the shielded pole head and the improvements in BER was about 2-3 orders of magnitude translating to a 200 kFCI improvement in linear density for the shielded pole design.

Samsung drive results using WD (formerly Read Rite) heads in 2003 were shown. Linear densities with good error rates appeared possible up to about 725 kBPI in these tests with an areal density of 63.8 Gbpsi.

Electronic Channels for Perpendicular Recording

Michael Madden from Marvell spoke about read channels for perpendicular recording. Madden said that the most important components for a PMR channel are:

- DC target programming
- Baseline correction loop
- Lowered preamp and input AC-coupled frequencies

Perpendicular recording waveforms have a spectral distribution closer to a DC-full spectrum compared to longitudinal recording waveform spectra that are closer to DC-free spectra. The generalized PMR channel has a Continuous-Time Filter (CTF), an FIR equalizer and a Viterbi detector. The best coding for low error rate with the perpendicular signals were DC-full codes at lower noise power and a coding intermediate between DC-free and DC-full at higher noise levels. Thus an intermediate coding appeared to give the best overall performance.

Differentiating the head output attenuates much of the media noise and is insensitive to DC-offsets. However most of the perpendicular signal is concentrated at low frequency and signal power is reduced by differentiation. In addition differentiation gives an overall SNR loss and enhances the high frequency noise.

Baseline wander can be a problem with an undifferentiated perpendicular signal. A feedback loop can be designed into the read channel (or amplifier) to significantly reduce baseline wander. This can result in close to an order of magnitude improvement in BER. For perpendicular recording preamps the channel input AC-coupled HPF cut-off must be lowered as well as the preamp cut-off. Traditional preamps will not work well with DC-attenuated targets.

The dominant errors observed with perpendicular heads and media are single-bit errors. These errors can be detected using a single bit of parity which can be used to achieve better error correction. RLL codes can be used to limit the DC content of the bits, which also limits random data baseline wander. DC-limited codes have a lower code rate than traditional RLL codes. Marvel says that a well designed baseline loop can track DC wander such that the rate penalty of DC-limited codes is unnecessary. A DC-limited code can reduce the BER by up to an order of magnitude at higher noise attenuation factors.

Transition jitter is a dominate noise source in perpendicular recording. Sequences that contain many transitions will be noisier than sequences with few transitions. Thus transition jitter noise is correlated to the data pattern. A non-linear detector can de-correlate this data-dependent noise and improve BER compared to a linear detector.

The servo burst is differentiated by the analog front end with minimal performance loss from differentiated servo bursts. Most energy is away from DC in servo bursts with SNR higher than in data sectors. Thus DC-free codes can be used for servo signals without significant penalty.

German Feyh of Agere spoke on baseline wander compensation for long latency detectors. Feyh stated that perpendicular recording work was done by Agere with a full DC channel using a high pass filter in the preamplifier for fast write to read recovery. DC content in the data shifts the baseline but DC-free target patterns don’t need baseline compensation. Agere proposed a local and global decision feedback scheme to compensate for baseline wander.

In local feedback the path memory of each state is fed back to that state (baseline wander compensation is implemented for each state). In global feedback the path memory of the state with the best metric is fed back to all the states. In global feedback baseline wander compensation is implemented only once. Agere found that local and global feedback result in the same BER performance.

A High Performance Frequency Modulated (HPFM) code can also be used to reduce baseline wander where DC content is coded out, error propagation is limited, and coding is matched to the expected high pass filter. The result is worse-case patterns are permitted that could shift the baseline up to 29% zero to peak. Signal processing may be required to overcome detection latency. Much of the balance of the presentation discussed the details of the signal processing that could be applied.

Conclusion

Perpendicular recording appears to be close to leaving the research labs and meeting the demands of the real world incarnated in disk drives. The first commercial disk drives using perpendicular recording will likely be announced within the next couple of years. Perpendicular recording will be a major switch in magnetic recording enabling ever higher areal recording density.

The presentations of this seminar have shown some of the progress and known issues with perpendicular magnetic recording as well as the considerable work in many engineering laboratories to identify and eliminate these issues. Much progress has been made but it is clear that more needs to be done. Based on the innovative history of the hard disk industry I fully expect that the transition to perpendicular recording will occur soon. Perpendicular recording will be another step in the inherent quest of intelligent beings to create greater and ever more pervasive knowledge of the world we live in and pass that knowledge on to generations to come.

About the Author

Tom Coughlin, President, Coughlin Associates, has been working for over 20 years in the data storage industry at companies such as Ampex, Polaroid, Seagate, Maxtor, Micropolis, Syquest, 3M. He has over 50 publications and 6 patents to his credit. Tom is active with IDEMA, the IEEE Magnetics Society and is an adjunct professor at Santa Clara University. Tom is President of Coughlin Associates, which provides market and technology analyst as well as Data Storage Consulting services. For more information go to www.tomcoughlin.com.

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