SPRUSON&FERGUSON

Australia

Patents Act 1990

Notice Of Entitlement

I, Lee Dorset Pippard, of 31 Market Street, Sydney, New South Wales, 2000, Australia, being the Patent Attorney for the Applicant/Nominated Person in respect of Application No. 66263/94, state the following:-

The Applicant/Nominated Person has entitlement from the actual inventors as follows:

The Applicant/Nominated Person is the assignee of the actual inventors.

The Applicant/Nominated Person is entitled to rely on the applications listed in the Declaration under Article 8 of the PCT as follows:

The Applicant/Nominated Person is the assignee of the basic applicants.

The basic applications listed on the Declaration under Article 8 of the PCT are the first applications made in a Convention country in respect of the invention.

DATED this 27th Day of May 1997

L D Pippard

IRN: 315560:LDP:PWM

Instructor Code: 060933

[N:\LIBT]23728:BPD

AU9466263

(12) PATENT ABRIDGMENT (11) Document No. AU-B-66263/94
(19) AUSTRALIAN PATENT OFFICE (10) Acceptance No. 680498

(54) Title
METHOD AND APPARATUS FOR NOISE REDUCTION IN MAGNETIC MEDIA

International Patent Classification(s)
(51)[5] G06K 007/08 G11B 027/36 G11B 005/035

(21) Application No. : 66263/94 (22) Application Date : 05.04.94

(87) PCT Publication Number : WO94/24639

(30) Priority Data

(31) Number	(32) Date	(33) Country
046040	09.04.93	US UNITED STATES OF AMERICA
046071	09.04.93	US UNITED STATES OF AMERICA
208997	10.03.94	US UNITED STATES OF AMERICA

(43) Publication Date : 08.11.94

(44) Publication Date of Accepted Application : 31.07.97

(71) Applicant(s)
WASHINGTON UNIVERSITY

(72) Inventor(s)
RONALD SCOTT INDECK; MARCEL WETTSTEIN MULLER; JOSEPH ANDREW O'SULLIVAN

(74) Attorney or Agent
SPRUSON & FERGUSON , GPO Box 3898, SYDNEY NSW 2001

(56) Prior Art Documents
US 4837426
US 4806740

(57) Claim

1. A method for writing a noise compensated source signal onto a magnetic medium with a device having a conventional recording transducer, said method comprising the steps of:

continuously determining the remanent noise of said magnetic medium as said magnetic medium is traversed by a conventional recording transducer, said remanent noise being represented by an analog electrical signal;

continuously compensating said source signal for said remanent noise as said remanent noise is determined; and

writing said compensated source signal on said magnetic medium;

wherein the step of determining includes the steps of:

saturating said magnetic medium; and

reading said remanent noise from said saturated magnetic medium.

.../2

11. A method for determining a benchmark in a magnetic medium, said method comprising the steps of:

saturating a portion of said magnetic medium; and

reading said saturated portion of said magnetic medium to thereby determine its remanent noise, said remanent noise being unique to said portion and therefore a benchmark identifying said portion.

CORRECTED VERSION*

PCT

page 2/3, drawings, replaced by a new page bearing the same number; after rectification of obvious errors as authorized by the International Searching Authority

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : G06K 7/08, G11B 5/035, 27/36

A1

(11) International Publication Number: WO 94/24639

(43) International Publication Date: 27 October 1994 (27.10.94)

(21) International Application Number: PCT/US94/03722

(22) International Filing Date: 5 April 1994 (05.04.94)

(30) Priority Data:

08/046,040	9 April 1993 (09.04.93)	US
08/046,071	9 April 1993 (09.04.93)	US
08/208,997	10 March 1994 (10.03.94)	US

(71) Applicant: WASHINGTON UNIVERSITY [US/US]; One Brookings Drive, St. Louis, MO 63105 (US).

(72) Inventors: INDECK, Ronald, Scott; 729 Gralee Lane, Olivette, MO 63132 (US). MULLER, Marcel, Wettstein; 4954 Lindell Boulevard, St. Louis, MO 63108 (US). O'SULLIVAN, Joseph, Andrew; 7321 Northmoor Drive, St. Louis, MO 63105 (US).

(74) Agent: HAFERKAMP, R.; Rogers, Howell & Haferkamp, Suite 1400, 7733 Forsyth Boulevard, St. Louis, MO 63105 (US).

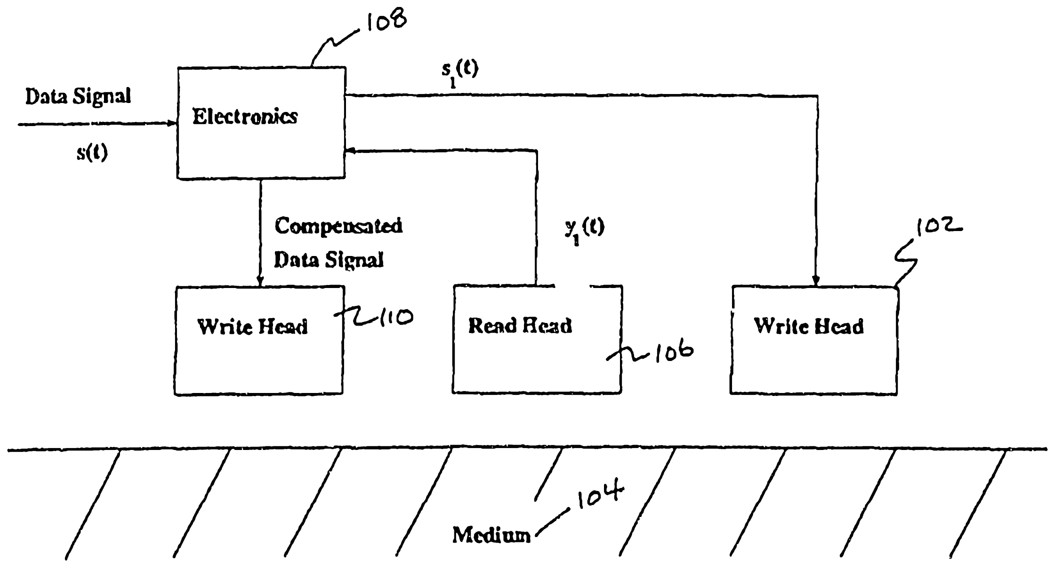
(81) Designated States: AU, BB, BG, BR, BY, CA, CZ, FI, HU, JP, KP, KR, KZ, LK, MG, MN, MW, NO, NZ, PL, PT, RO, RU, SD, SK, UA, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published

With international search report.

680498

(54) Title: METHOD AND APPARATUS FOR NOISE REDUCTION IN MAGNETIC MEDIA



(57) Abstract

A method and apparatus is disclosed for determining the remnant noise in a magnetic medium (104) by DC saturation (102) of a region thereof and measurement (106) of the remaining DC magnetization. Conventional recording transducers may be used to determine the remnant noise. Upon determination, the remanent noise may then be compensated for in either or both of the record (110) and playback modes for all varieties of magnetic media including videotapes, cassette tapes, etc.

* (Referred to in PCT Gazette No. 27/1994, Section II)

METHOD AND APPARATUS FOR NOISE REDUCTION IN MAGNETIC MEDIA

Background and Summary of the Invention

The sources of noise in a readback signal from a magnetic recording medium have been investigated and identified. One of those sources includes the irregularities and defects in the microstructure of the magnetic medium itself. For many years, the noise generated from this source has been thought, as with the noise generated from other identified sources, to be random and subject only to statistical analysis for its determination. The inventors herein have recently demonstrated that this noise component is instead deterministic, ie. is permanent and repeatable, depending entirely on the transducer-medium position and on the magnetic history of the medium. As confirmed by experiments conducted by the inventors herein, when the medium has had no signal written on it and has been recorded only with DC fields, the observed readback signals are almost identical. The magnetic contribution to the readback signal under these conditions results from spatial variations in the medium's magnetization: magnetic domains, ripple, local fluctuations of the anisotropy field and saturization magnetization. These local properties, in turn, are affected by the morphology and magnetic properties of the individual grains which make up the domain and which do not change after deposition. Hence, the noise from a nominally uniformly magnetized region measured at a fixed position on a magnetic medium is reproducible. As shown by the inventors herein, a magnetic medium may be DC saturated and its output then measured to determine its remanent state or remanent noise. The inventors have confirmed that this remanent noise is a function of the magnetic microstructure by comparing the remanent noise after a positive DC saturation with the remanent noise after a negative DC saturation. It has been found that these wave forms are virtual "mirror images" of each other thereby demonstrating a close correlation. Similarly, other methodologies were used to confirm that the remanent noise was determinative, repeatable, and related to the physical microstructure of the magnetic medium itself. Remanent noise arising from the permanent microstructure exhibits identifiable features characteristic of that permanent microstructure after practically any magnetic history. See *Spatial Noise Phenomena of Longitudinal Magnetic Recording Media* by Hoinville, Indeck and Muller, IEEE Transactions on Magnetics, Volume 28, No. 6, November 1992, the disclosure of which is incorporated herein by reference.

The inventive technique disclosed and claimed herein relies upon the discovery that the microscopic structure of the magnetic medium itself is a permanent random arrangement of microfeatures and therefore deterministic. In other words, once fabricated, the recording medium's physical microstructure remains fixed for all conventional recording processes. In particulate media, the position and orientation of each particle does not change within the binder for any application of magnetic field; in thin film media, the microcrystalline orientations and grain boundaries of the film remain stationary during the record and reproduce processes. It is the magnetization within each of these fixed microfeatures that can be rotated or modified which forms the basis of the magnetic recording process. If a region of a magnetic medium is saturated in one direction by a large applied field, the remanent magnetization depends strongly on the micro-structure of the medium. This remanent state is deterministic for any point on the recording surface. Each particle or grain in the medium is hundreds to thousands of Angstroms in dimension. Due to their small size, a small region of the magnetic surface will contain a very large number of these physical entities. While the fabrication process normally includes efforts to align these particles, there is always some dispersion of individual orientations. The actual deviations will be unique to a region of the medium's surface making this orientation deterministic and making its effects susceptible to elimination. As can be appreciated by those of ordinary skill in the art, noise reduction enables increase in storage capacity, increase in data rates, and eases the burden on transducers, medium, and system design and fabrication.

Although this discovery has been made by the inventors herein, noise reduction techniques based on this discovery have not been implemented. As this noise component of remanent noise is deterministic, it may be reliably repeated and measured at any particular point on a magnetic medium. Accordingly, the inventors have developed several techniques which take advantage of this fact for producing uncorrupted pre-recorded signals which may be played back by any playback device but which, when played back, have already been compensated for the remanent noise component. In other words, a magnetic recording may be recorded at the factory with a signal which has been first compensated for remanent noise such that as the signal is played back later the playback signal or read signal has the remanent noise component virtually eliminated. As the remanent noise component may very well be the most significant factor in noise emanating from pre-recorded magnetic media, this noise reduction technique may very well provide a dramatic reduction in noise with no required modification to the tremendous number of playback machines presently in the public's hands. This would include playback machines for the entertainment industry, etc. In a first embodiment of the invention, the remanent noise is first determined and the recording device compensates the original signal for the remanent noise before writing the compensated signal on the magnetic medium. These steps may be readily achieved with conventional recording transducers, as explained herein. Consequently, very little, if any, modification to existing recording equipment need be made to achieve these noise compensated recordings.

A second methodology will also create uncorrupted pre-recorded signals on magnetic medium. With this method, the signal is first written on the magnetic medium, the written signal is then read from the magnetic medium, this read signal is then compared with the original signal. The differences therebetween are determined to be noise, the greatest component of which is deterministic medium noise. The original signal is compensated to eliminate this noise before being recorded back at the same location on the magnetic medium. Thus, after the compensated signal has been recorded onto the magnetic medium, any other readback or playback machine would then produce a signal which has been compensated for remanent noise.

In still another embodiment of the present invention, the inventors have developed a methodology for compensating a signal read from a magnetic medium for remanent noise in real time. This methodology permits a playback device to be manufactured and sold which can play back pre-recorded magnetic medium which has not itself been compensated prior to recording, and produce a signal which is compensated on readback. With this method, the signal is first read from the magnetic medium, the remanent noise is determined for said magnetic medium, such as by saturating the magnetic medium and reading the remanent noise directly therefrom, and the signals are then compared to eliminate the noise from the original corrupted signal prior to use. As determining the remanent noise, as envisioned by the inventors, involves destroying the original recorded signal when the medium is saturated, another step to the method may well include re-recording either the original signal or its compensated counterpart. Thus, with this methodology, a playback device may take a pre-recorded magnetic medium whose signal has not been compensated, and transform it into a magnetic medium with a compensated signal recorded thereon such that further playbacks of the same magnetic medium would possibly not require compensation. With this methodology, if implemented in one alternative embodiment thereof, a user with a suitable playback machine may very well transform his entire collection of recorded media from non-compensated to compensated magnetic media. In other words, one may readily convert a collection of analog cassette tapes having original non-compensated signals thereon to a collection of analog cassette tapes having compensated signals recorded thereon which may then be played back by any playback device and produce what should be an enhanced signal because of the noise reduction.

In essence, the present invention is elegantly simple and adapted for implementation by conventional recording transducers as are commonly found and used in virtually every read or read/write device presently utilized by the public at large. Such examples include cassette players, magneto-optic disc players, and VCRs. In its simplest implementation, a conventional recording transducer need merely DC saturate a specified portion of a magnetic medium, and then "read" or "play back" the remanent noise which remains. This remanent noise, which is an analog signal, may then be used to compensate an original signal, such as a musical program, dramatic reading, etc.

While the principal advantages and features of the invention have been described above, and a number of examples given, a greater understanding of the invention may be attained by referring to the drawings and the description of the preferred embodiment which follow.

<u>Brief Description of the Drawings</u>

Figure 1 is a magnified representative depiction of the microscopic structure of a region of magnetic medium;

Figure 2 is a magnified depiction of several tracks of a magnetic medium having microscopic structure representatively shown thereon;

Figure 3 depicts three conventional recording transducers and a magnetic medium traveling thereunder;

Figure 4 is a perspective view of a magneto-optic disc player with a magneto-optic disc in its tray;

Figure 5 is a cassette player depicting a cassette tape for play therein;

Figure 6 is a perspective view of a VCR with a tape ready for insertion;

Figure 7 is a schematic dia ram of the write-read-write embodiment of the inventio and

Figure 8 is a block diag of the electronics shown in Figure 7.

Detailed Description of the Preferred Embodiment

As shown in Figure 1, a region of magnetic medium 20 is built up with a plurality of microcrystalline structures 22 in a random pattern. This microcrystalline structure 22 is comprised of particles or grains varying from hundreds to thousands of Angstroms in diameter. The view of Figure 1 is greatly enlarged and magnified in order to depict this physical phenomena. As shown in Figure 2, this microcrystalline structure extends throughout the magnetic medium even though the magnetic medium 24 shown in Figure 2 may be itself comprised of tracks 26, 28, 30 as well known in the art.

Referring now to Figure 3, a plurality of conventional recording transducers 32, 34, 36 are shown mounted in a transducer transport 37 with a traveling magnetic medium 38 controllably driven past recording transducers 32, 34, 36 all as is well known in the art. Recording transducers 32-36 are all connected to electronic circuitry 40, as well known in the art, to control and read their input and output and further process signals for playback or other use. Although only three transducers 32, 34, 36 are being shown in Figure 3, it will be well understood to those of ordinary skill in the art that a plurality of recording transducers of any number may just as easily be provided and, as taught herein, may be required in order to effect the purposes of the present invention. In implementing the present invention, the recording transducers 32-36 as shown in Figure 3 may be considered as part of a device which is used to create pre-recorded magnetic medium with remanent noise compensated recordings. Alternately, the device shown in Figure 3 may be considered as a playback unit of either a specialized playback device with means for creating a remanent noise compensated signal from a non-compensated pre-recorded signal, or a standard playback device which may be used to play back a remanent noise compensated magnetic medium. All of these functions are achieved with conventional recording transducers and therefore are readily implemented using existing and available technology.

A remanent noise compensated signal may be pre-recorded onto a magnetic medium by utilizing the following method. The remanent noise of the magnetic medium may first be determined by DC saturating the medium and then reading the remanent noise with a conventional recording transducer. This would take transducer 32 to saturate the medium and transducer 34 to read the remanent noise. The original signal would then be compensated, using conventional compensation circuits as is well known in the art to modify the original signal such that it may then be recorded by recording transducer 36. In this manner, using this method and device as shown in Figure 3, a pre-compensated recording, pre-compensated for remanent noise, may be created on magnetic medium 38. While there is a fixed and close spacing between transducers 32-36, the remanent noise is itself capable of being used for indexing the transducers 32-36 to thereby ensure that the compensated signal is recorded by transducer 36 for the remanent noise which in fact appears at that point on the magnetic medium for which said compensation has been made. This is because, as explained earlier herein, while the remanent noise is random, it is unique to any particular point on the magnetic medium and thus can be used to identify such point for benchmark purposes. While this is the perferred embodiment, it should be understood that the remanent noise is always there, whether the medium has been recorded over or not. Therefore, it is not strictly necessary that the specified portion of medium containing the remanent noise be DC saturated, or DC saturated in the same polarity in order to obtain the remanent noise.

In a variation of the first embodiment hereof, still another methodology may be used to create a pre-recorded magnetic medium having a signal recorded thereon which is remanent noise compensated. This second embodiment involves the steps of first writing the original signal on the magnetic medium, such as for example by transducer 32 in Figure 3, reading the recorded signal from said magnetic medium such as by transducer 34, comparing the read signal with the original signal to determine the differences therebetween, compensating the original signal, and then writing the compensated signal with transducer 36. Using this methodology, as with the first embodiment of the present invention, magnetic medium 38 would thus receive a recorded signal which has been compensated for the remanent noise inherent in the magnetic medium 38. These compensated recordings may then be played back by any conventional playback device and produce a signal which is noise compensated. This is important as with this implementation of this embodiment, uncorrupted copies or noise compensated copies of pre-recorded signals may be produced and made available for play back by the large number of playback devices already in the public's hands. This could very well be implemented for improving the pre-recorded playback of musical and dramatic programs on magneto-optic discs, cassette tapes (analog and digital), and VCR video tapes.

The inventors have developed a generalized model with an algorithm for implementing the write-read-write embodiment of the present invention. This generalized model is explained in Exhibit A. As noted therein, and referring to Figure 3 thereof, this generalized model compensates for additive medium noise and explains a design approach for implementing this embodiment with a silicon tap delay line. As shown in Figure 3 of Exhibit A, the signal $s_1(t)$ is processed by a write head, represented by h(t) onto a magnetic medium. As it is written, the signal is corrupted by two kinds of medium noise, non-repeatable medium noise $n_1(t)$ and repeatable additive medium noise $n_d(t)$. This corrupted signal is then read by a read head which processes it as represented by a function g(t). In order to determine the error function portion of the signal, the signal $s_1(t)$ is processed as represented by a function b(t) which is the equivalent of a write and read function, and then subtracted from the output of the read head. Additionally, an electronics noise signal $w_1(t)$ is added to represent the electronics noise. The result is an error function e(t) which is representative of the total noise introduced in the signal $s_1(t)$ by a write and read function. Next, the error function e(t) is then processed by a filter function c(t) which is the inverse of the noise expected to be added by a later write and read function. Finally, the output of the filter function c(t) is subtracted from the data signal (t) and a write head processes this signal with the function h(t) to record it onto a magnetic medium where it again suffers corruption through the two kinds of magnetic medium noise, repeatable additive medium noise $n_d(t)$ and also non-repeatable medium noise $n_2(t)$. At this point in the model, a signal desired to be recorded, s(t) has been recorded in a precompensated manner as the function c(t) subtracts out the effects of the write function, a later expected read function and the expected repeatable additive medium noise $n_d(t)$. As the magnetic medium is then read by a read head and the signal processed with the function g(t), a signal output y(t) is produced which is clearly compensated for.

Computer simulations have been run on this methodology utilizing the mathematical solutions for the various components of the system. As indicated at page 9 of

Exhibit A as well as Figures 5-7 of Exhibit A, the precompensation model disclosed therein with the write-read-write scheme yields a reduction in noise power on average. The amount of the reduction depends on the ratio between the repeatable noise power and all other noise. A distribution of noise powers is shown in Exhibit Figure 5 for 1,000 runs demonstrating the significantly decreased noise levels expected for recording with signal precompensation. Exhibit Figures 6 and 7 further demonstrate the improved signal wave form which is also achieved.

Further explanation of this write-read-write embodiment of the present invention is found in Figures 7 and 8. As shown in Figure 7, a first write head 102 writes the signal $s_1(t)$ on the medium 104. The recorded signal is then read by read head 106 which produces an output $y_1(t)$ to an electronics circuit 108, as explained in Figure 8. The electronics 108 produces a compensated data signal which is then written by write head 110 back on the magnetic medium 104. The write head 110 thus writes a precompensated version of the data signal s(t) which, after being read by another read head (not shown) produces an output of data signal s(t) which has been compensated for additive repeatable magnetic noise.

As shown in Figure 8, the electronics 108 includes an adder 112 which subtracts an output signal d(t) from ideal channel 114 having a function b(t) which processes the diagnostic signal $s_1(t)$ as equivalent to a write and read function. Diagnostic signal generator 115 processes the data signal s(t) to produce the diagnostic signal $s_1(t)$. For example, $s_1(t)$ could be a DC saturation signal. The output of adder 112 produces an error signal e(t) which is then compensated by compensation filter 116 through a signal transformation function c(t). As explained above, the compensation filter function c(t) is the inverse of the noise expected to be added by a write and read function. A second adder 118 subtracts the output of compensation filter 116 from the data signal s(t) to produce a signal which corresponds to a pre-compensated data signal for writing onto the magnetic medium by write head 110. As noted above, the generalized model and algorithm for each of the functions included in Figures 7 and 8 may be readily determined by one of ordinary skill in the art from the equations given in Exhibit A.

In still another implementation of the noise compensation methodology of the present invention, a playback device may be manufactured and sold which is capable of producing a noise compensated signal from recordings on magnetic media which have not been noise compensated. In this embodiment of the present invention, the signal is first read, such as by recording transducer 32 in Figure 3, the remanent noise is then determined such as by saturating the magnetic medium with a signal from transducer 34 and reading the remanent noise with transducer 36, and then the original signal would be compensated with said remanent noise prior to playback or other processing. Although not specifically shown, a fourth transducer may be provided to re-record either the original signal or the compensated signal back on the magnetic medium 38 for subsequent playback. With this device and method, conventional recordings on magnetic media may be compensated for remanent noise prior to playback. Also, perhaps while being played, magnetic media may be transformed from uncompensated to noise compensated recordings. Thus, with this implementation, a device may be made and sold for use with the vast inventory of pre-recorded magnetic media presently in the public's hands.

In still another implementation of the present invention, the unique remanent noise pattern may be used as a benchmark to locate a transducer at a particular position in a magnetic medium. For example, for editing purposes, and as previously explained above, the conventional recording transducers 32-36 as shown in Figure 3 could be readily used to determine the remanent noise at a particular position on the magnetic medium 38. This could then be used to reposition the transducers 32-36 at the start or finish of an edit, or otherwise to precisely position a conventional recording transducer with respect to the magnetic medium. This application would provide significant advantages in dubbing, etc. which is commonly used for taking rough cuts of many kinds of programs and editing them for final production. For that matter, editing is used in a large number of applications too numerous to mention herein. In each of these applications, it is desired to accurately and reliably reposition a recording transducer to ensure the continuity of the signal and program through the discontinuity created by the editing process. As the inventors' methodology provides a convenient and simple way to most accurately determine the exact position on a magnetic medium, and to find that exact position, the present invention provides a unique and novel way to position a recording transducer for editing.

As shown in Figure 4, a magneto-optic disc player 64 has a magneto-optic disc 66 in its tray 68 ready for play. As explained herein, a magneto-optic disc player 64 may play back remanent noise compensated magneto-optic discs 66. Furthermore, although not presently commercially available for home use, magneto-optic disc players 64 may soon be available which are capable of recording onto magneto-optic discs 66. In such event, all of the embodiments of the present invention may be implemented such that magneto-optic discs 66 may be noise compensated when played back, even though its original signal was not recorded in a noise compensated format, and CD player 64 used to re-record a noise compensated signal back onto magneto-optic disc 66.

Similarly, a cassette player 72 as shown in Figure 5 has a cassette 70 being inserted therein for play. This magnetic medium is also susceptible to implementation of the inventors' methodologies to enhance the record and/or playback of cassette 70 in remanent noise compensated format.

A last example of an implementation of the inventors' methodologies is shown in Figure 6 and includes a VCR 74 with a video tape cassette 76 being inserted therein. As the video tape cassette 76 is a magnetic medium, it is also susceptible to the noise compensation methodologies disclosed and claimed herein.

There are various changes and modifications which may be made to the invention as would be apparent to those skilled in the art. However, these changes or modifications are included in the teaching of the disclosure, and it is intended that the invention be limited only by the scope of the claims appended hereto.

EXHIBIT A

Magnetic Recording System Design to Reduce Medium Noise Through Signal Precompensation

Joseph A. O'Sullivan
Dakshi Agrawal
Donald G. Porter
Ronald S. Indeck
Marcel W. Muller

Department of Electrical Engineering
Washington University
St. Louis, MO 63130

ABSTRACT

Much of the noise in magnetic recording systems is due to intrinsic properties of the magnetic medium itself. Much of this noise is repeatable in that identical waveforms recorded in the same place on the medium (with an erasure in between) have highly correlated noise. This effect is exploited in the present paper through the design of systems to estimate and subsequently correct the distortion of the recorded waveform due to medium noise. The approach may be applicable to other storage channels whose noise is medium dependent such as magneto-optic media. A method for optimally reducing repeatable additive medium noise is proposed. Simulations of this system have been run and the results are promising.

1. Introduction

Most models of magnetic recording channels use a traditional communication theory model as shown in figure 1. The channel is the magnetic medium. The medium may corrupt the signal, and if modeled as additive noise, average statistics of this medium noise may be estimated and used in system design to improve the performance of the system. Other sources of noise include receiver noise and head noise. Even when these latter two noise sources are considered, the medium noise limits the system performance. The authors have developed models for magnetic media [1,2] as have others [3,4,5,6,7]. These models account for the fact that medium noise arises from the microscopic properties of the recording medium. These properties are deterministic once the medium is manufactured. While it is infeasible to have a complete microscopic scan of the medium for use in signal design, it may be possible to measure local medium features on-line and to use those features when designing the recorded signal. This strategy accounts not only for the average effects of the medium, but also for local effects.

The proposed strategy is to make on-line measurements of the medium noise and then to use these measurements in signal design. Possible ways to accomplish this strategy are discussed below. They may be classified as "write-read-write" recording strategies. First a diagnostic signal is written on the medium, second the resulting magnetization pattern is read, and third an information carrying signal is recorded. The design of the second written signal depends on the model for the medium noise.

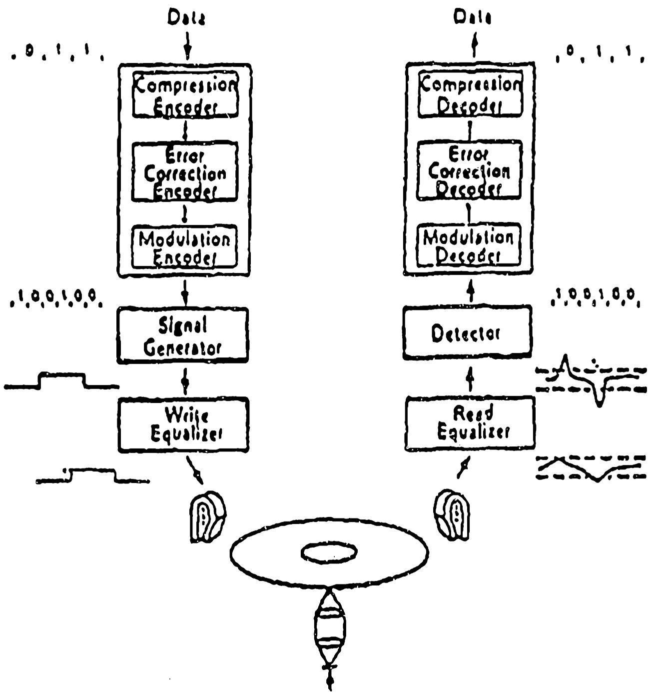


Figure 1. Traditional model for a magnetic recording system. This figure is from the Introduction to the Special Issue on Coding for Storage Devices, IEEE Transactions on Information Theory, vol. 37, May 1991, p. 709.

There is no generally accepted model for the medium noise. There is some evidence that the medium noise has a large multiplicative portion. This does not adequately account for medium noise when the medium is demagnetized, however. Some initial simulations using our medium model indicate greater variability of the written magnetization in the demagnetized case than when a strong unidirectional magnetic field has been applied. This seems to be consistent with measurements from magnetic media. It should be noted that the noise in the demagnetized case is correlated with the previous signal written; however, presently we are not including previously written signals when modeling the magnetization resulting from writing a new signal. While our medium model has been useful for computing the capacity of magnetic media, it has not yet been used for designing magnetic recording systems. Presently our medium model is being used to analyze medium noise in received voltage waveforms [8].

The approach here is based on simplified models for the effects of medium noise. As we gain experience with this approach and as more sophisticated models become available, we will use them.

2. Write-Read-Write Precompensation: Additive Noise Case

We begin the analysis for this scheme with a linear approximation to the recording process. Recognizing that the process is inherently nonlinear, we anticipate that the approach presented here must be improved by using a more accurate nonlinear model for the recording system. Due to the speed of electronics, the approach proposed holds the possibility of being implemented in silicon.

Shown in Figures 2 is a block diagram description of the write-read-write recording process. Figure 2 shows three heads flying over a magnetic medium. The first records a diagnostic signal $s_1(t)$. The second reads the resulting magnetization on the medium. Third, a signal that has been computed by the electronics and includes the desired signal and compensation for the medium noise is written onto the medium. When the information is read at a later time, the signal-to-noise ratio will be significantly higher, resulting in better recovery of the desired signal. The crucial design of the electronics block is based on a model for the manner in which the medium noise is manifested. The discussion in this paper is based on an additive model for the medium noise.

Shown in Figure 3 is an approximate linear model of a magnetic recording system. In this system, all blocks are assumed to be linear and time-invariant, all random processes are assumed to be wide-sense stationary. A diagnostic signal $s_1(t)$ is written using the write head ($h(t)$), medium noise is added ($n_d(t)+n_1(t)$), the signal is read ($g(t)$) introducing electronics noise ($w_1(t)$). There may be an equalizer in the system and this is incorporated into $h(t)$ or $g(t)$ as appropriate. The desired channel response is $d(t)$. We assume here that $b(t)=(g * h)(t)$ (where * denotes convolution). Denoting the output of $g(t)$ plus $w_1(t)$ by $y_1(t)$, the error signal $e(t)=y_1(t)-(b * s_1)(t)$ equals the part of the received voltage waveform due to system noise. The noise has a repeatable component, $n_d(t)$, due to the medium, and two unrepeatable components, $n_1(t)$ due to the medium, and $w_1(t)$ due to the electronics. The goal is to compensate for the repeatable component. To do this, $e(t)$ is filtered, subtracted from $s(t)$, the information-bearing signal to be recorded, then recorded with the write head again. Physically, a signal is written on the medium then read; the desired signal, $d(t)$, computed electronically, is subtracted from this signal producing the error signal $e(t)$; then the new signal $(s(t)-(c * e)(t))$ is written at the same place on the medium.

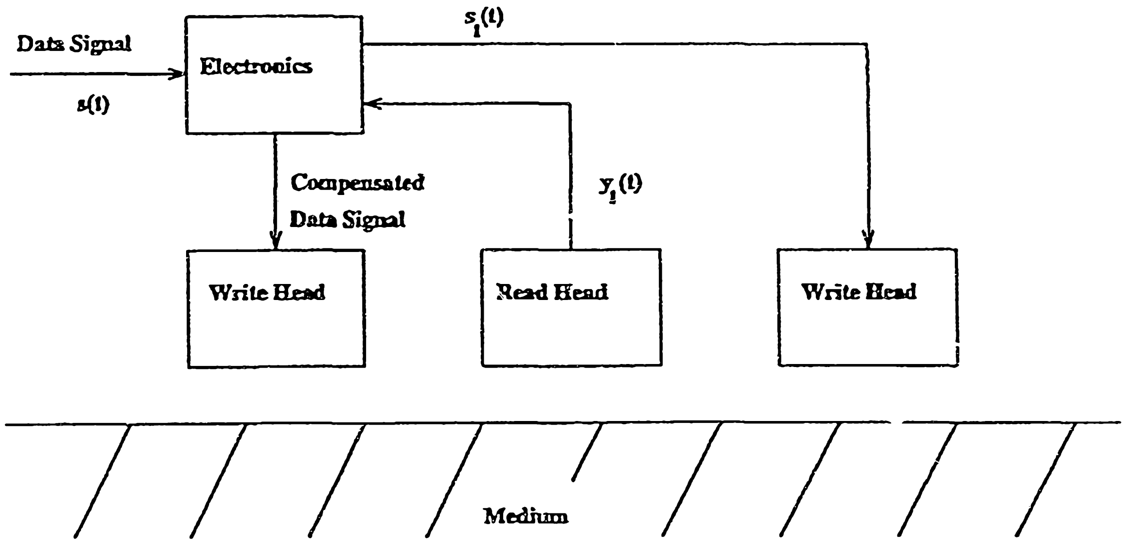


Figure 2. Block diagram description of the write-read-write recording process.

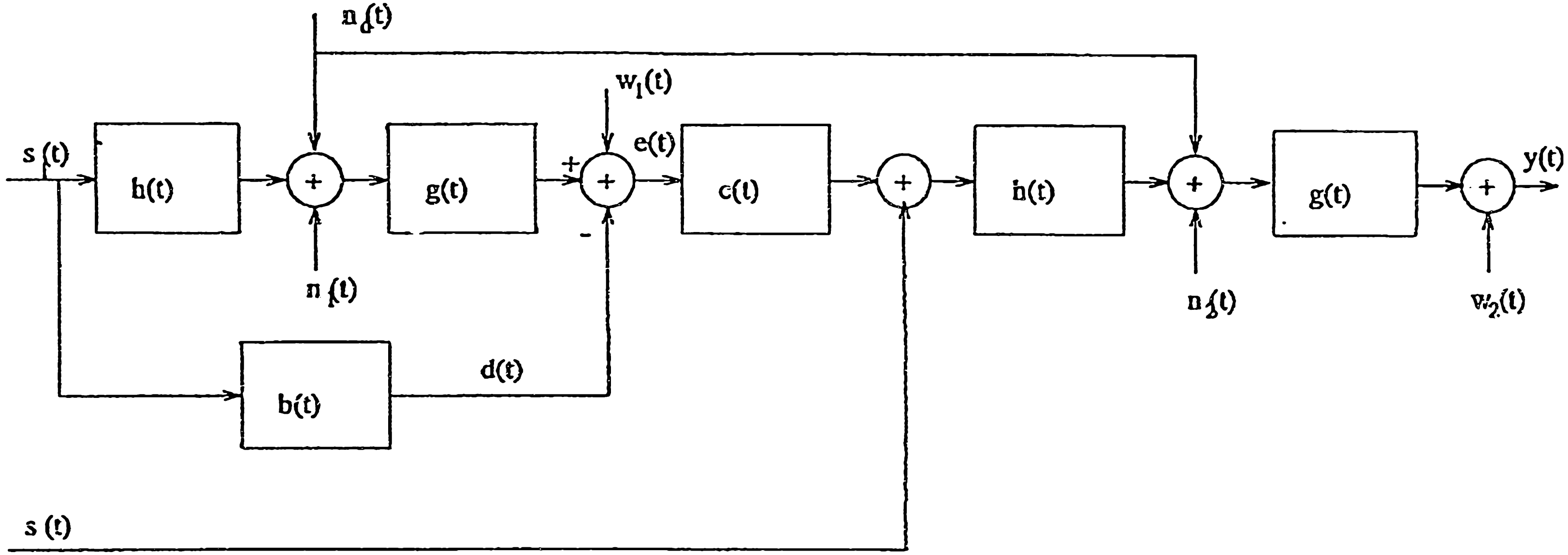


Figure 3. Approximate linear model for the magnetic recording channel. This model includes wide sense stationary additive Gaussian noise components. There are two input signals s1(t), a diagnostic signal, and s(t), an information bearing signal. The repeatable medium noise is nd(t).

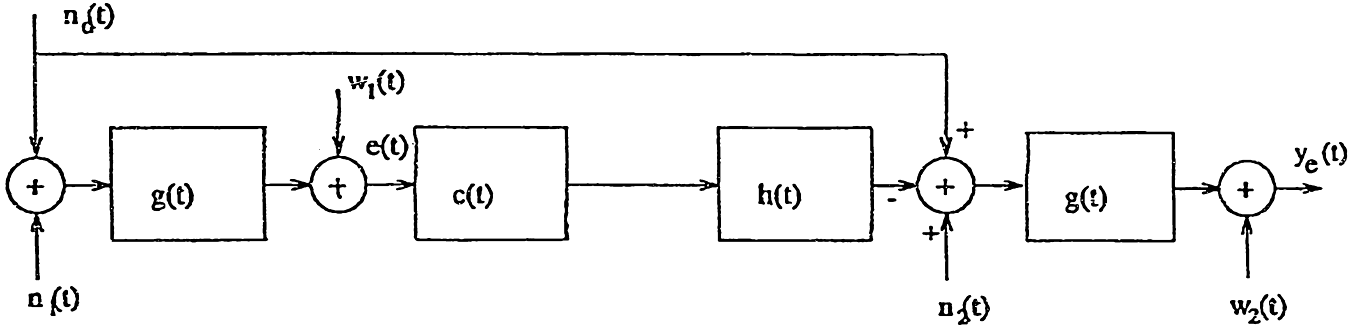


Figure 4. Noise model for figure 3. The input signals have been removed so that only the noise signals that are used in the design of c(t) are shown.

The design problem may be stated as minimizing the distortion in the waveform $y(t)$ that is eventually read due to the repeatable component of medium noise. From this viewpoint, $c(t)$ may be designed from the reduced system shown in Figure 4. In that figure, the information-bearing signal $s(t)$ and the diagnostic signal $s_1(t)$ have been removed. Let the distortion be measured in terms of noise power. Then the goal is to design $c(t)$ to minimize the signal power in $y_e(t)$, the noise component of the output. For any real system design, there will be a constraint class, **C**, for the $c(t)$ so that they are realizable. A typical constraint is that it be the output of a transversal filter with a fixed number of taps. The problem statement becomes

$$\min_{c \in \mathbf{C}} E[|(g * n_d)(t) - (g * h * c * e)(t)|^2]. \tag{1}$$

For many constraints, the problem reduces to solving the well-known normal equations.

To minimize (1), substitute

$$e(t) = y_1(t) - s_1(t) = w_1(t) + (g * (n_1 + n_d))(t)\ . \tag{2}$$

Computing the expected value, the problem statement (2) reduces to

$$\min_{c \in \mathbf{C}}[(c * \bar{c} * q)(0) - 2(\bar{c} * p)(0)]\ , \tag{3}$$

where for any signal $f(t)$, $\bar{f}(t) = f(-t)$,

$$q(t) = (b * \bar{b} * (R_{ww} + g * \bar{g} * (R_{dd} + R_{nn})))(t), \tag{4}$$

$$p(t) = (g * \bar{b} * R_{dd})(t), \tag{5}$$

$$b(t) = (g * h)(t),$$

and $R_{ww}(t)$, $R_{nn}(t)$, and $R_{dd}(t)$ are the autocovariance functions for $w_i(t)$, $n_i(t)$, and $n_d(t)$, respectively ($i = 1$ or 2).

The unconstrained solution to (3), if it exists is

$$c_u(t) = P(\omega)/Q(\omega)\ , \tag{6}$$

where $P(\omega)$ and $Q(\omega)$ are the Fourier transforms of $p(t)$ and $q(t)$, respectively, and the subscript u in $c_u(t)$ represents the fact that this is an unconstrained optimum solution. This may not exist because $Q(\omega)$ may have zeros. Also, even if this solution exists, it may not be realistically realizable. Usually some type of constraint is added so that the solution for $c(t)$ exists and is well-behaved (easily realizable). In the following section, the constraint of the solution being implementable by a tapped delay line (and thus easily realizable using standard VLSI design) is added.

Notice that if all noise were additive and Gaussian, and the unconstrained solution (6) is used, then the limiting increase in capacity is determined by the change in the power spectrum of the channel. As opposed to using a standard writing scheme, the component due to the repeatable medium noise is attenuated. This attenuation increases as the energy of the repeatable component increases relative to the energy of the unrepeatable component. That is, if the power spectrum due to the noise in an uncompensated system is $S_y(\omega) = S_r(\omega) + S_u(\omega)$, where $S_r(\omega)$ is the repeatable component, then the power spectrum of the compensated system is

$$S_{y_e}(\omega) = S_u(\omega) + S_r(\omega)\frac{S_u(\omega)}{S_r(\omega) + S_u(\omega)}\ . \tag{7}$$

Note that $S_u(\omega) = |G(\omega)|^2 S_{nn}(\omega) + S_{ww}(\omega)$ and $S_r(\omega) = |G(\omega)|^2 S_{dd}(\omega)$; here S_{ww}, S_{nn}, and S_{dd} are the Fourier transforms of R_{ww}, R_{nn}, and R_{dd}, respectively. The capacity of the Gaussian channel is then increased; the increase depends on the spectral shapes (that is, system factors such as the $g(t)$, $h(t)$, and the noise levels) and detailed analysis of the standard water-filling capacity formula [9, p. 267]. In our experimental setup, depending on the medium tested, we have found that the repeatable component is one half to nine tenths the total noise power. If all of the repeatable medium noise is adequately modeled as additive noise, equation (7) implies a potential increase in signal to noise ratio of 1.2 to 7.2 dB.

3. Tapped Delay Line Implementation

As mentioned in the previous section, the actual implementation would be different from (6). Some realizability constraint must be imposed. One natural constraint (but not the only possible one; other constraints have been considered and the following derivation can easily be modified to account for other constraints) is that the implementation be realized by a tapped delay line. Tapped delay lines (finite impulse response filters with a finite number of coefficients) may be easily built using VLSI technology.

The constraint class is the set of $c(t)$ such that

$$c(t) = \sum_{n=-n}^{N} c[n]\delta(t - nT), \qquad (8)$$

where δ is a Dirac delta function, and T is the time interval between the taps. Let for each integer n, let

$$p[n] = p(nT) \quad \text{and} \quad q[n] = q(nT). \qquad (9)$$

The solution for the optimal tap weights is obtained by substituting the form (8) for $c(t)$ into (3), then taking the derivatives with respect to the tap weights $c[n]$. This results in a set of $2N+1$ equations in the $2N+1$ unknown tap weights $c[n]$. The equations are

$$\sum_k q[n-k]c[k] = p[n], \text{ for } -N \le n \le N. \qquad (10)$$

If the values of $c[n]$ and $p[n]$ are put into vectors $\mathbf{c}$ and $\mathbf{p}$, and the values of $q[n]$ are put into the matrix $\mathbf{Q}$ such that the n,k entry of $\mathbf{Q}$ is $q[n-k]$, then equation (10) may be rewritten compactly as

$$\mathbf{Q}\mathbf{c} = \mathbf{p}. \qquad (11)$$

This equation may be solved directly to give

$$\mathbf{c}_{opt} = \mathbf{Q}^{-1}\mathbf{p}. \qquad (12)$$

Alternatively, symmetry properties of q, c, and p may be exploited to reduce the computational complexity of the matrix inversion required in (12). These symmetry properties may be stated compactly as $q[n] = q[-n]$ and $p[n] = -p[-n]$; these imply that the solution for c is odd symmetric so $c[n] = -c[-n]$.

4. Simulations

In this first simulation we made many simplifying assumptions. We assume that the impulse response function $h(t)$ of the write head is $\delta(t)$ and the unit step response function of the read head is a Lorentz pulse. We also assume that head mechanism is precise enough to let us write at a predecided position on the medium.

We assume that all noise sourses are white and Gaussian. Additive repeatable media noise, head noise and electronic noise are assumed to have total noise power distributed among themselves in the ratio of 8:1:1. Total noise power is 10% of the the signal power.

The step response of the read head is given by

$$s(t) = \frac{1}{1+\left(\frac{2t}{TS}\right)^2}$$

Here $TS/2$ is the half width of the Lorentz pulse. Differentiating this with respect to t we get the impulse response function $g(t)$ of the read head

$$g(t) = \frac{-\left(\frac{8t}{T^2S^2}\right)}{\left[1+\left(\frac{2t}{TS}\right)^2\right]^2}.$$

Taking the Fourier transform of $g(t)$, we get

$$G(f) = -jaf\exp(-b|f|)$$

where

$$a = -\pi^2 TS \quad \text{and} \quad b = \pi TS.$$

Let the sampling rate be $f_s(=K/T)$. Then the energy in the frequencies greater than $f_s/2$ gets aliased. Thus the total aliased energy is

$$E_a(f_s) = 2\int_{\frac{f_s}{2}}^{\infty} |G(f)|^2 df$$

$$= v\exp(-X)\left[1 + X + \frac{X2}{2}\right]$$

where $v = \pi/(2TS)$ and $X = f_s b = \pi SK$, K being the number of times ($f_s = K/T$) a bit is being sampled. From the graph of $E(X)$ versus X, it can be concluded that for $X = 12$ less than 0.1% energy gets aliased.

In our simulation we choose $S = 1/\pi$, which represents a fairly high linear density and we choose $K = 10$, at which less than 0.3% of the energy of $g(t)$ and less than 4% of the energy of a square wave get aliased. The percentage of the energy of the square wave that gets aliased is high for $K = 10$, however it does not matter in this simulation since by exploiting linearity of the system, we can compute noise powers independently of the signal. Note that $g[n]$, the discretized version of $g(t)$ is nonzero even for large $|n|$. However it is monotonically decreasing in magnitude. For our simulation we have truncated $g[n]$ suitably in such a manner that the truncated $g[n]; -8 \leq n \leq 8$; has more than 99% of the energy of the original nontruncated $g[n]$. Tap weights in the filter $c[n]$ were computed assuming $-16 \leq n \leq 16$.

Simulation results show that under above stated assumptions write-read-write scheme yields 4.74 dB reduction in noise power on the average. Figure 5 compares the noise powers before and after signal precompensation obtained in 1000 runs. Figures 6 and 7 show typical read waveforms obtained by writing the signal without and with compensation.

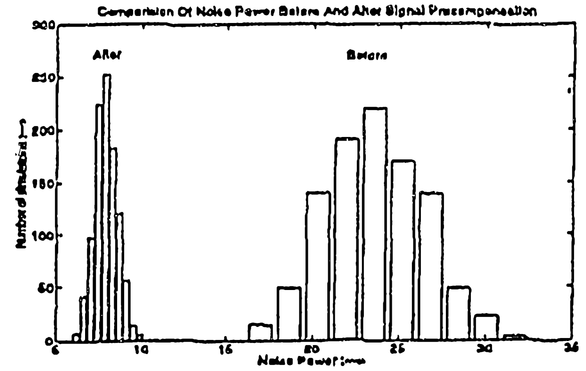


Figure 5: Comparision between read noise before and after signal precompension

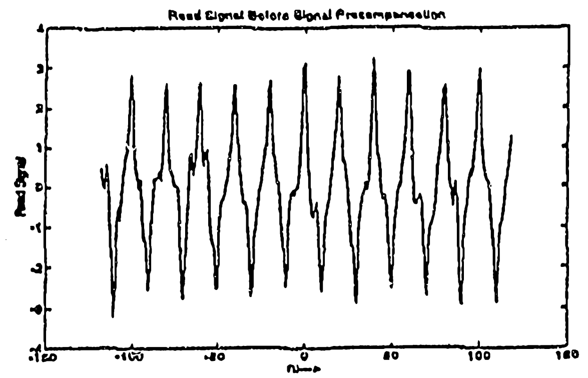


Figure 6: Read signal before signal precompension

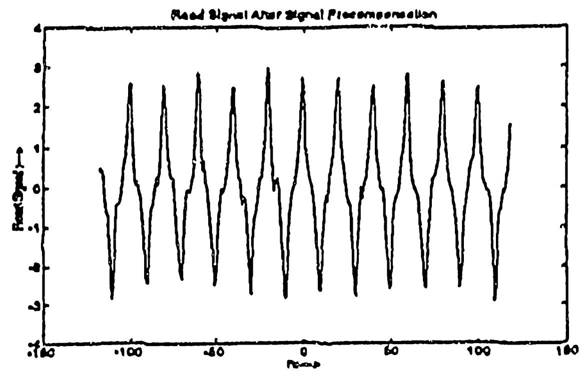


Figure 7: Read signal after signal precompension

5. Conclusions

Recently, experiments have demonstrated that medium noise has a repeatable component [10]. In this summary we have outlined a strategy for precompensating for local medium effects that are additive through the use of a write-read-write recording protocol. We have also explored the use of more sophisticated models for the effects of medium noise, including multiplicative effects. Initial studies show that for multiplicative noise, the relatively simple analysis presented above is not adequate. While estimates of the effects of the multiplicative and additive components may be estimated, their optimal use in signal compensation is complicated.

References

1. J. A. O'Sullivan, D. G. Porter, R. S. Indeck, and M. W. Muller, "Physically Based Information Science of Magnetic Recording I. Information Capacity of a Medium Model," *IEEE Trans. Magnetics*, vol. 29, 1993.
2. J. A. O'Sullivan, D. G. Porter, R. S. Indeck, and M. W. Muller, "Recording Medium Properties and Capacity Bounds," *J. Applied Physics*, 1993.
3. M. Mansuripur and R. Giles, "Simulation of the Magnetization-Reversal Dynamics on the Connection Machine," *Computers in Physics*, vol. 5, pp. 291-302, 1991.
4. R. Giles and M. Mansuripur, "Possible Sources of Coercivity in Thin Films of Amorphous Rare Earth-Transition Metal Alloys," *Computers in Physics*, vol. 5, pp. 204-219, 1991.
5. H. N. Bertram and J. Zhu, and H. Ehrenreich and D. Turnbull, eds., *in Solid State Physics*, Academic Press, New York, 1992.
6. J. Zhu and H. N. Bertram, "Micromagnetic Studies of Metallic Thin Films," *Journal of Applied Physics*, vol. 63, pp. 3248-3253, 1988.
7. J. Zhu and H. N. Bertram, "Magnetization Reversal in CoCr Thin Films," *Journal of Applied Physics*, vol. 66, pp. 1291-1307, 1989.
8. J. A. O'Sullivan, D. G. Porter, R. S. Indeck, and M. W. Muller, "Physically Based Information Science of Magnetic Recording II. Physical Models for Medium Noise," *submitted to IEEE Trans. Magnetics*, 1994.
9. R. Blahut, *Principles and Practice of Information Theory*, Addison Wesley, Reading, MA, 1987.
10. J. R. Hoinville, R. S. Indeck, and M. W. Muller, "Spatial Noise Phenomena of Longitudinal Magnetic Recording Media," *IEEE Trans. Magnetics*, vol. MAG-28, pp. 3398-3406, 1992.

The claims defining the invention are as follows:

1. A method for writing a noise compensated source signal onto a magnetic medium with a device having a conventional recording transducer, said method comprising the steps of:

continuously determining the remanent noise of said magnetic medium as said magnetic medium is traversed by a conventional recording transducer, said remanent noise being represented by an analog electrical signal;

continuously compensating said source signal for said remanent noise as said remanent noise is determined; and

writing [illegible]d compensated source signal on said magnetic medium;

wherein the step of determining includes the steps of:

saturating said magnetic medium; and

reading said remanent noise from said saturated magnetic medium.

2. The method of claim 1, wherein said device includes three aligned recording transducers and wherein the step of saturating is implemented with one of said recording transducers, the step of reading is implemented with another of said recording transducers, and the step of writing is implemented with the third of said recording transducers.

3. The method of claim 2, further comprising the step of:

indexing said recording transducers with said remanent noise to thereby write said compensated source signal at the point on said magnetic medium where said remanent noise has been compensated for.

4. A method for writing a noise compensated source signal onto a magnetic medium with a device having a conventional recording transducer, said method comprising the steps of:

continuously determining the remanent noise of said magnetic medium as said magnetic medium is traversed by a conventional recording transducer, said remanent noise being represented by an analog electrical signal;

continuously compensating said source signal for said remanent noise as said remanent noise is determined; and

writing said compensated source signal on said magnetic medium;

further comprising the steps of:

first writing said source signal onto said magnetic medium; and

reading said source signal from said magnetic medium.

5. The method of claim 4, wherein the step of determining the remanent noise includes the step of comparing said read source signal with the source signal as first written.

6. A method for creating a magnetic medium with a source signal written thereon which, when read, has already been compensated for the remanent noise in said magnetic medium, the method comprising the steps of:

writing said source signal on said magnetic medium;

reading said source signal from said magnetic medium;

compensating said source signal for the differences between it and said read source signal, said differences being indicative at least in part of the remanent noise of said magnetic medium; and

writing said compensated source signal onto said magnetic medium and at the same location thereon as originally written.

7. A method for continuously compensating a source signal as it is read from a magnetic medium for the remanent noise of said medium, said method comprising the steps of:

continuously reading said source signal from said magnetic medium;

continuously determining the remanent noise of said magnetic medium; and

continuously compensating said source signal for said remanent noise as it is read from said magnetic medium.

8. The method of claim 7, wherein the step of determining further comprises the steps of:

saturating said magnetic medium; and

reading said saturated magnetic medium to thereby determining its remanent noise.

9. The method of claim 8, wherein the step of determining the remanent noise is performed closely after the step of reading said source signal so that said source signal may be compensated in a relatively short time delay.

10. A method for compensating a source signal read from a magnetic medium for the remanent noise of said magnetic medium in real time, said method comprising the steps of:

reading said source signal from said magnetic medium with a recording transducer;

saturating said magnetic medium with a second recording transducer, said second recording transducer being aligned with and closely spaced behind said first recording transducer to thereby saturate said magnetic medium after only a short time delay from reading;

reading said saturated magnetic medium with a third recording transducer to thereby continuously determine the remanent noise thereof, said third recording transducer being aligned with and closely spaced behind said second recording transducer to thereby determine said remanent noise after only a short time delay from saturating; and

continuously compensating said source read signal with said remanent noise signal as both said signals are generated to thereby continuously produce a compensated source signal in real time.

11. A method for determining a benchmark in a magnetic medium, said method comprising the steps of:

saturating a portion of said magnetic medium; and

reading said saturated portion of said magnetic medium to thereby determine its remanent noise, said remanent noise being unique to said portion and therefore a benchmark identifying said portion.

12. A magnetic medium having a compensated source signal recorded thereon made by implementing a method comprising the steps of:

writing a source signal on said magnetic medium;

reading said source signal from said magnetic medium;

compensating said source signal for the differences between it and said read source signal, said differences being indicative at least in part of the remanent noise of said magnetic medium; and

writing said compensated signal onto said magnetic medium and at the same location thereon as originally written.

13. A device for compensating a signal read from a magnetic medium for the remanent noise of said magnetic medium, said device including:

means for reading said signal from said magnetic medium with a first recording transducer;

means for saturating said magnetic medium with a second recording transducer, said second recording transducer being aligned with and closely spaced behind said first recording transducer to thereby saturate said magnetic medium after only a short time delay from reading;

means for reading said saturated magnetic medium with a third recording transducer to thereby continuously determine the remanent noise thereof, said third recording transducer being aligned with and closely spaced behind said second recording transducer to thereby determine said remanent noise after only a short time delay from saturating; and

means for continuously compensating said read signal with said remanent noise signal as both said signals are generated to thereby continuously produce a compensated signal in real time.

14. A method for pre-compensating a data signal for a remanent noise comprising the steps of:

recording a diagnostic signal on a portion of a magnetic medium, reading said portion of magnetic medium having the diagnostic signal recorded thereon,

computing a compensation signal from the read of said portion of magnetic medium,

computing a source signal for recording using said compensation signal, and

recording said source signal on said portion of magnetic medium.

15. The method of claim 14, wherein the step of computing the compensation signal includes the step of computing a repeatable noise component of said portion of magnetic medium.

16. The method of claim 15, wherein the step of computing a repeatable noise component includes the step of computing a repeatable noise component corresponding to a remanent noise of said portion of magnetic medium.

17. The method of claim 16, wherein said remanent noise is additive, and the step of computing the repeatable noise component corresponding to said remanent noise includes the step of subtracting a desired signal response for said diagnostic signal from the read of said portion of magnetic medium.

18. The method of claim 14, wherein the step of recording the diagnostic signal includes the step of recording with a first write head, the step of reading said portion of magnetic medium includes the step of reading with a second read head, and the step of recording the source signal includes the step of writing with a third write head, all of said heads being substantially aligned to sequentially traverse the same portion of magnetic medium.

19. The method of claim 14, wherein the step of computing the source signal includes the step of subtracting the compensation signal from a data signal desired to be recorded.

20. A method for pre-compensating a source data signal desired to be recorded for a remanent noise comprising the steps of:

writing a source diagnostic signal on a portion of magnetic medium with a first write head, reading said magnetic medium portion having the diagnostic signal written thereon with a second read head,

electronically synthesizing a compensation signal by processing the read of said magnetic medium portion and the source diagnostic signal,

electronically synthesizing a recordable data signal by processing said compensation signal and said source data signal, and

recording said recordable data signal with a third write head.

21. The method of claim 20, wherein all of said heads are substantially aligned with a direction of head travel so that said heads sequentially traverse the same portion of magnetic medium.

22. The method of claim 21, wherein the step of synthesizing a compensation signal includes the process of convolution.

23. The method of claim 22, wherein the step of synthesizing a recordable data signal includes the step of subtracting said compensation signal.

24. The method of claim 23, wherein the step of subtracting includes the step of subtracting said compensation signal from the source data signal.

25. The method of claim 19, wherein the data signal desired to be recorded is used as the diagnostic signal.

26. The method of claim 19, wherein the diagnostic signal is a DC saturation signal.

27. The method of claim 14, further comprising the step of reading a prerecorded signal from the portion of the magnetic medium upon which the diagnostic signal is subsequently recorded, wherein the step of computing a source signal for recording includes computing said source signal using the read of said prerecorded signal.

28. The method of claim 20, wherein the source data signal desired to be recorded is used as the source diagnostic signal.

29. The method of claim 20, wherein the source diagnostic signal is a DC saturation signal.

30. The method of claim 20, further comprising the step of reading the source data signal from said magnetic portion with a fourth read head.

31. A write-read-write device substantially as described herein with reference to Figs. 7 and 8 of the accompanying drawings.

DATED this Twenty-third Day of May 1997
Washington University
Patent Attorneys for the Applicant
SPRUSON & FERGUSON

FIG. 1.

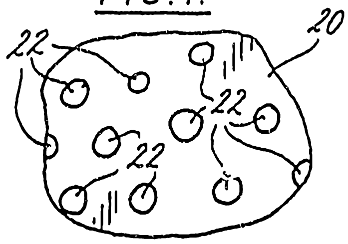


FIG. 2.

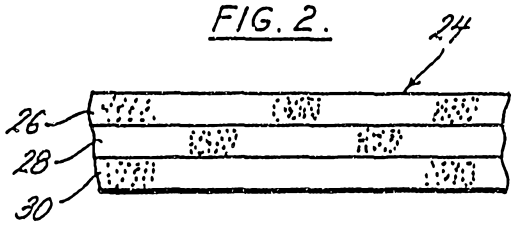


FIG. 3.

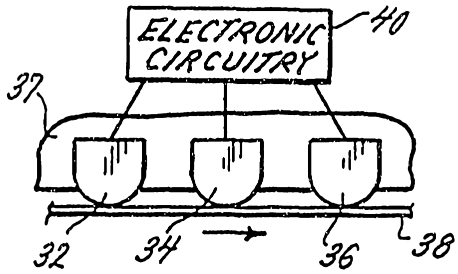
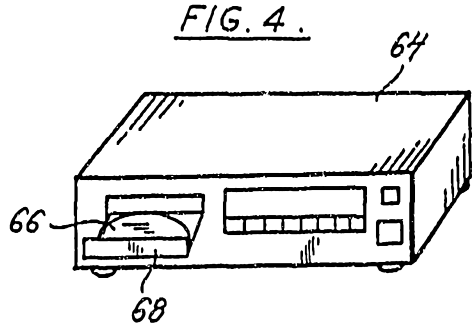
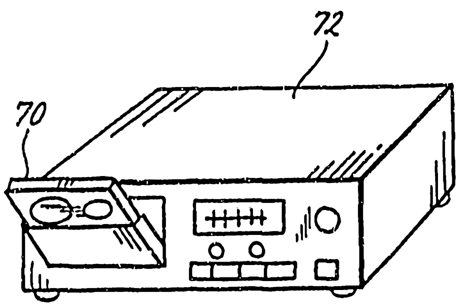


FIG. 4.





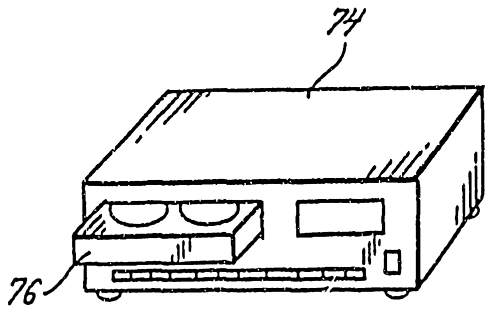


FIG. 5.

FIG. 6.

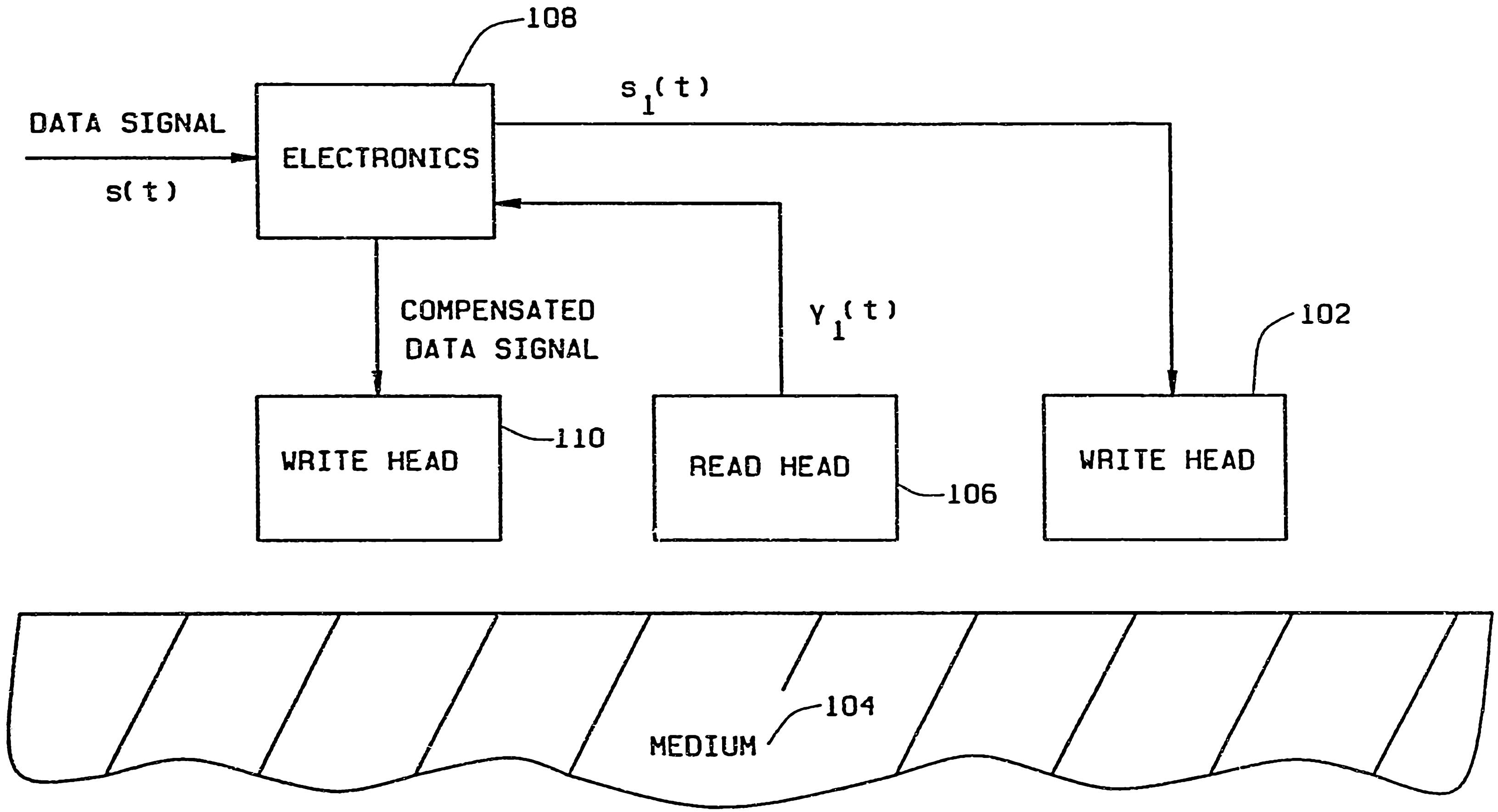

108
DATA SIGNAL
s(t)
ELECTRONICS
s1(t)
COMPENSATED
DATA SIGNAL
Y1(t)
102
WRITE HEAD
110
READ HEAD
106
WRITE HEAD
MEDIUM
104

FIG. 7

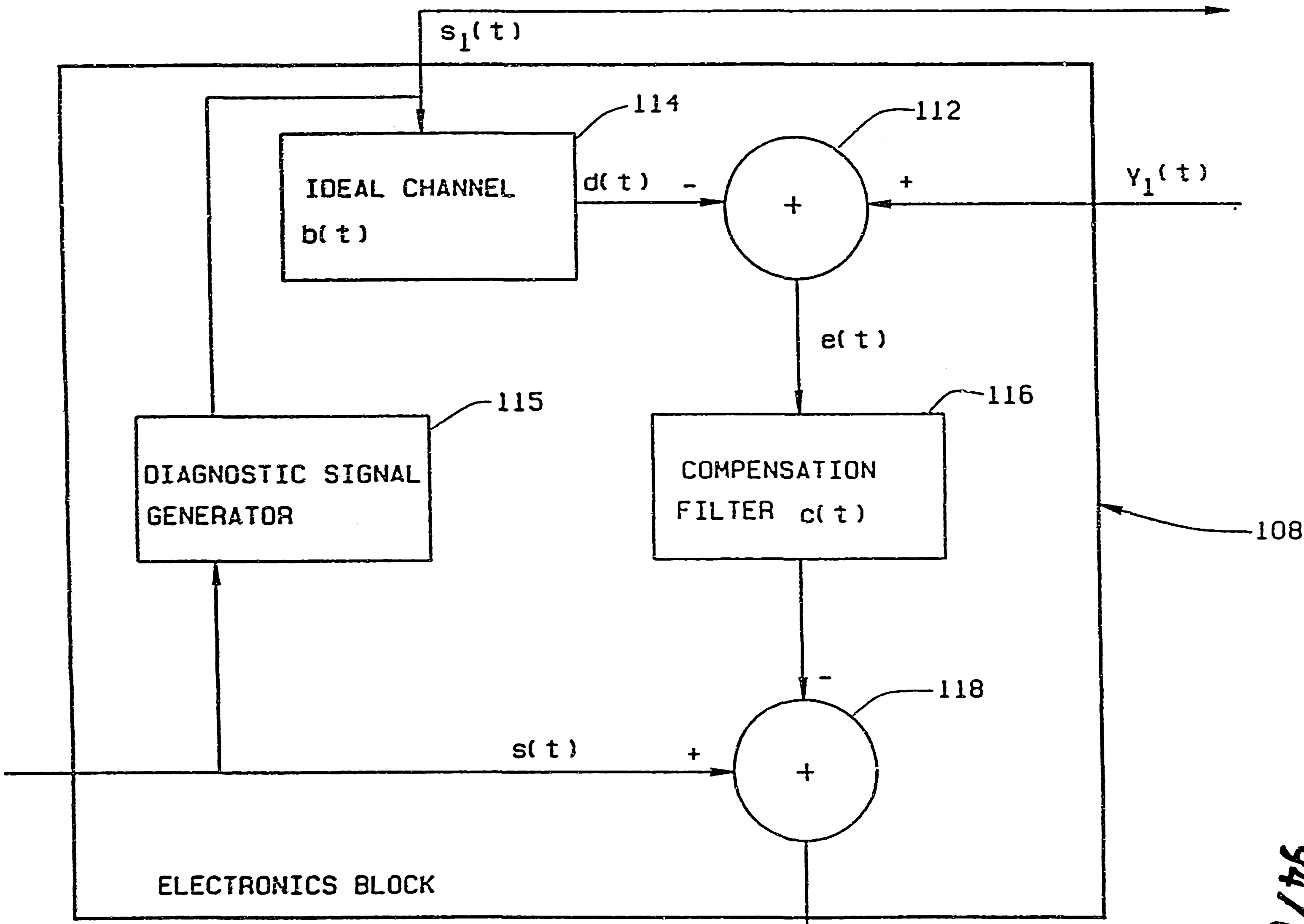


FIG. 8

PCT/US 94/03722
IPEA/US 08 NOV 1994

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/03722

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :Please See Extra Sheet.
US CL :380/3; 360/65, 31; 235/449
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 380/3; 360/65, 31; 235/449

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,806,740 (GOLD, ET AL) 21 February 1989	1-15
A	US, A, 4,837,426 (PEASE, ET AL.) 06 June 1989	1-15

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 JULY 1994	02 AUG 1994

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	DAVID CAIN
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0463

INTERNATIONAL SEARCH REPORT

national application No.
PCT/US94/03722

A. CLASSIFICATION OF SUBJECT MATTER:
IPC (5):

G06K 7/08;G11B 5/035,27/36