Characterization of Magnetic Oxide Recording Media Using Fourier Analysis of Static Hysteresis Loops

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Abstract

A technique for characterizing the entire static hysteresis loop using Fourier analysis has been developed. The method goes beyond the familiar listing of saturation moment, squareness, coercivity, and switching field distribution to describe the magnetization process in detail. The essence of the technique is to "unfold" the static hysteresis loop by plotting the moment as a function of applied field over one complete field cycle and then to take the Fourier transform of the resulting waveform. The procedure is repeated for a series of minor loops taken with increasing values of maximum field until saturation is achieved and the dependence of the harmonic content on maximum field is used to differentiate among various oxide recording media. Several additional applications of the Fourier transform method, including characterization of the temperature dependence of hysteretic properties and analytic expressions for accurate loop reconstruction, are described.

Introduction

The characterization of magnetic materials based upon hysteresis loop measurements generally involves a small set of familiar parameters consisting of the saturation moment m_s, the squareness S, the coercivity H_c, and the switching field distribution S^*. This description neglects additional information about the magnetization process which is contained in the hysteresis loop and which, prior to now, was not easily extracted. The situation has changed in that the data may now be readily taken in digital fashion and subsequently manipulated by computer. With the digital implementation in mind, the obvious technique for characterizing the entire loop is the use of Fourier analysis. Previous efforts along these lines were primarily theoretical and did not demonstrate the utility of the method.[1,2] In the present work, a measurement scheme for characterizing particulate recording media using the Fourier method is discussed and examples are presented.

Experimental Details

Data are taken using a modified EG&G Princeton Applied Research vibrating sample magnetometer (VSM) interfaced to a Hewlett Packard 9836C computer which controls the apparatus and performs the data analysis. In operation, the hysteresis loop is digitized, stored on disk, and then analyzed using either the discrete Fourier transform (DFT) or fast Fourier transform (FFT). The FFT is just a very efficient numerical scheme of calculating the DFT and either method produces equivalent results. The choice of which transform to use depends upon the experimental conditions in that the FFT algorithm requires that the number of moment values be a power of 2 and that the moment values be separated by equal magnetic field intervals. In the context of this paper, Fourier transform (FT) will be taken to mean either DFT or FFT.

← Fig. 1

The essence of the method is to measure a static loop, Fig. 1(a), starting at some maximum magnetic field H_{max}, then "unfold" the loop as shown in Fig. 1(b). Here the values of the moment are plotted as a function of applied field over one complete field cycle starting at $+H_{max}$. The FT method is applied to the moment waveform producing a Fourier cosine series, Fig. 1(c), having only odd harmonics as given in Eq. (1).

$$m(h) = m_s \sum A_n \cos(nh + \phi_n) \qquad \text{(for odd n)} \qquad (1)$$

where $h = 90(1 - H/H_{max})$ for H starting at $+H_{max}$ and going to $-H_{max}$ and where $h = 90(3 + H/H_{max})$ for H continuing from $-H_{max}$ back to $+H_{max}$. In the present characterization method, this procedure is repeated for a series of loops taken with the field applied along the particle orientation/tape velocity direction with $(H_{max}/H_c) = 1, 1.5, 2, 3,$ and 6. The sample is demagnetized prior to each loop excursion. By specifying

H_{max} and the resulting Fourier amplitudes and phases, the entire hysteresis loop may be described. Comparison between samples with different values of H_c and magnetic moment is facilitated by normalizing the harmonic amplitudes with respect to the fundamental component amplitude, A_1.

← FIG.2

Results and Discussion

A typical series of loops taken at different values of H_{max} is shown in Fig. 2. For clarity, the data for $H_{max} = 2H_c$ and $6H_c$ are not included. The sample is a piece of Ampex 721 high energy recording tape whose properties are listed in Fig. 5. Figs. 3(a) and 3(b) illustrate the dependence of the harmonic amplitudes and phases for this sample on the value of (H_{max}/H_c). Although the software routinely computes many more harmonics, the behavior for only the first five odd harmonics (n = 1, 3, ..., 9) is shown. In general, the number of harmonics retained depends upon the end use of the analysis, i.e., sample comparison, loop reconstruction, or detailed characterization. The accuracy of the FT description of the hysteretic behavior is quantitatively shown in Fig. 4 where, for the above example, the root mean square deviation between the actual loop data and the FT results is plotted as a function of the number of harmonics used. The points shown span the range from the smallest to the largest value of H_{max} employed. Using only the first five odd harmonics produces an error which ranges from 0.6% for $H_{max} = H_c$ to 6% for $H_{max} = 6H_c$. The reason for this behavior is that as (H_{max}/H_c) increases, the loop becomes "squarer" and has higher harmonic content.

← FIG.3, FIG.4

A principal use for the present FT method has been to provide a quantitative comparison among different samples of magnetic oxide recording tapes. Fig. 3(b) shows that the field dependence of the phase becomes more striking with increasing harmonic number but the amplitudes become too small to be of practical value. For purposes of comparison, the field dependence of the amplitude in the H_{max} region between H_c and $3H_c$ has the most significance. At higher values of H_{max}, the amplitudes of all samples approach the values of a square wave (whose harmonic amplitudes vary like n^{-1}). Fig. 5 illustrates the H_{max} dependence of the first 3 odd components for several oriented and one unoriented (ISOMAX) media. The latter has a distinctly different behavior from that of the oriented samples, i.e., a monotonic increase in (A_3/A_1) and (A_5/A_1) as opposed to the more complicated dependence of the oriented samples in the region of H_{max} between H_c and $2H_c$.

← FIG.5

This FT characterization method has been used to distinguish among various lots of ostensibly the same tape. It is sensitive enough to show that where the saturation moment has been intentionally reduced by the manufacturer by 25%, the remaining magnetic properties, as revealed by Fourier analysis, were identical to those of the original tape. This led to the conclusion that only the coating thickness had been altered and not the composition of the coating. Alternately, where two samples having the same M_s and H_c originating in different lots were characterized, the FT method revealed significant differences between them.

← FIG. 6

Another use for the FT method is to characterize changes in the same sample under different experimental conditions. This is illustrated in Fig. 6 where the field dependence of the Fourier amplitudes at different temperatures is shown. The data refer to an ISOMAX sample with properties listed in the figure. Although the coercivity changes by almost a factor of four over this range and the squareness changes by 17%, the present characterization procedure gives a concise, analytic description of the variation in loop shape. While the (A_3/A_1) field dependence just shifts downward with increasing temperature, the (A_5/A_1) behavior is somewhat more complicated with the development of a minimum in the data at $H_{max} = 2H_c$ at the highest temperature. Over this temperature range, the magnetization reversal process is dominated by the crystalline anisotropy and the FT method may afford the means of understanding the details of the reversal mechanism.[3]

← FIG. 7, FIG. 8

The FT method can also be used to provide an analytic description of the hysteretic process. In this application, the technique yields an accurate, analytic expression which may be incorporated into calculations for more realistic modelling of magnetic phenomena. Figs. 7 and 8 illustrate the actual and the Fourier reconstructed loops for 2 samples having vastly different hysteretic behavior. Fig. 7 describes an ISOMAX sample with the applied field perpendicular to the plane of the sample. The shearing effect of the demagnetizing field reduces the harmonic content of the loop which can be represented with an accuracy of 1% using only the first and third harmonics ($A_1 = 1.08m_s$, $\phi_1 = 344^o$; $A_3 = 0.115m_s$, $\phi_3 = 122^o$). Fig. 8 refers to the sample described earlier in Fig. 2 with $H_{max} = 6H_c$. The high squareness (0.79) of the loop and the large value of (H_{max}/H_c) require a considerable number of harmonics to achieve the 2% accuracy shown here. In this instance, the first ten odd harmonics are used in the reconstruction and their values are listed in the figure. The "wiggles" in the reconstructed loop have the periodicity of the highest harmonic component.

Future work involves the application of stress, temperature, and compositional changes to determine the effect on the hysteretic properties as monitored by the FT method. The aim of this effort is a deeper understanding of the magnetization process. Such an understanding is dependent upon a precise method for characterizing the magnetic behavior and work thus far indicates that the FT analysis is such a method. The FT method also enhances the portability of hysteretic data. At present, hysteretic data circulates in the technical community either in the form of the familiar magnetic parameters or as actual loop traces. With the FT method, it is possible to distribute hysteretic information by tabulating the harmonic content of a series of loops.

Conclusions

A technique, using Fourier analysis of hysteresis loops to characterize magnetic oxide recording media with greater accuracy than previously possible, is now available. This method owes its existence and ease of implementation to digital instrumentation techniques. In this work, it has been used to compare different particulate recording media, characterize the temperature dependence of hysteretic behavior, and provide analytic expressions for static hysteresis loops. It may have wider applications in the future as a sensitive probe of magnetization processes and also as an efficient means for transmitting detailed hysteretic data.

References

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4. R. M. Josephs, D. S. Crompton, and C. S. Krafft, "Orientational Variation of Hysteretic Properties in Particulate Recording Media," to be presented at the '86 INTERMAG Conference.

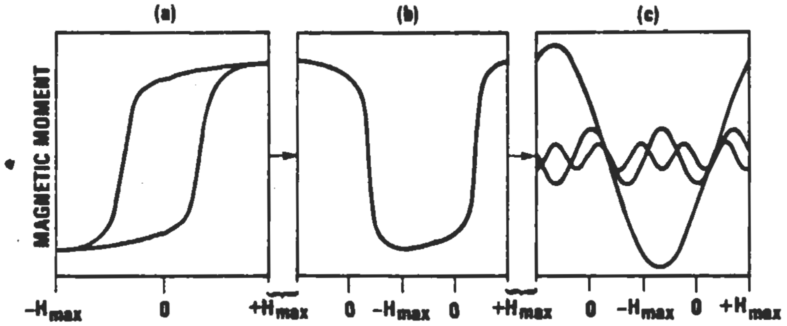


Figure 1. Decomposition of Hysteresis Loop Into Fourier Components

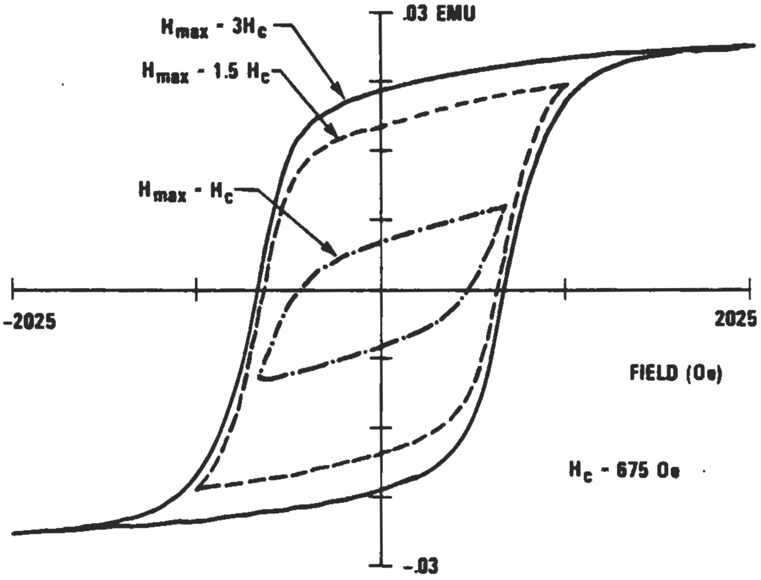


Figure 2. Loops For Different Values of H_{max}

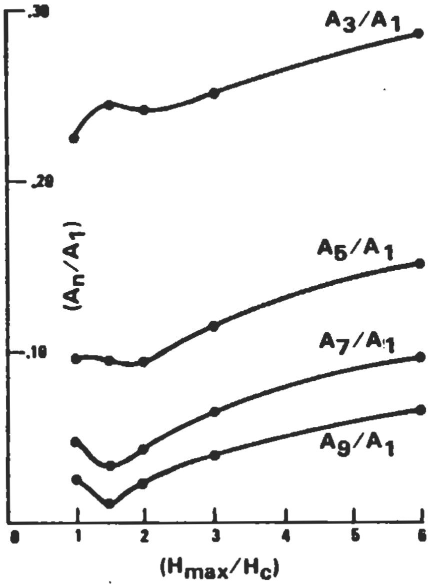


Figure 3(a). Dependence of Harmonic Amplitudes on H_{max} for Sample Described in Fig. 2

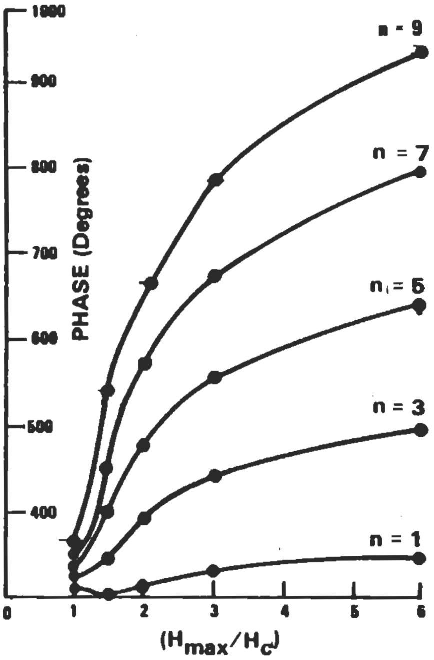


Figure 3(b). Dependence of Harmonic Phases on H_{max} for Sample Described in Fig. 2

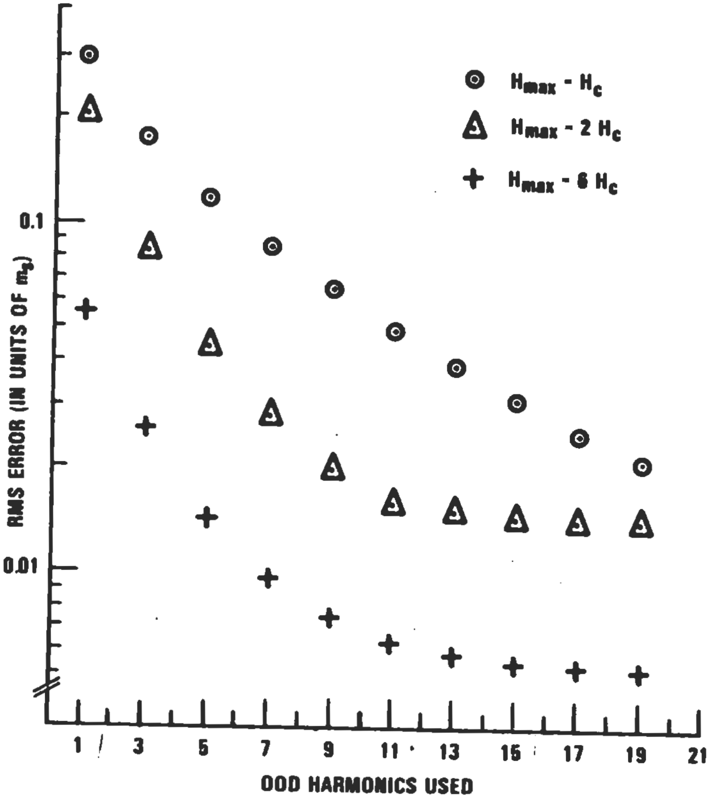
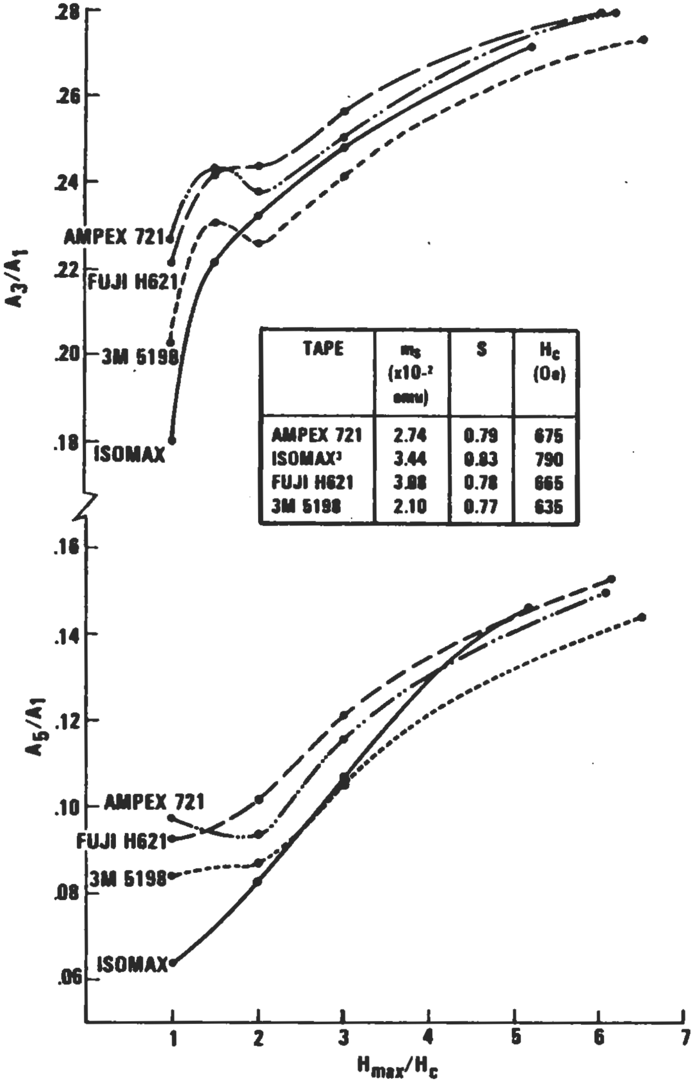


Figure 4. RMS Deviation of Fourier Transform From Actual Data As A Function of the Odd Harmonics Usad.



TAPE	m_s ($\times 10^{-2}$ emu)	S	H_c (Oe)
AMPEX 721	2.74	0.79	675
ISOMAX[3]	3.44	0.83	790
FUJI H621	3.88	0.78	665
3M 5198	2.10	0.77	635

Figure 5. H_{max} Dependence of A_3/A_1 and A_5/A_1. For Differant High Energy Recording Media.

MOMENT (emu)

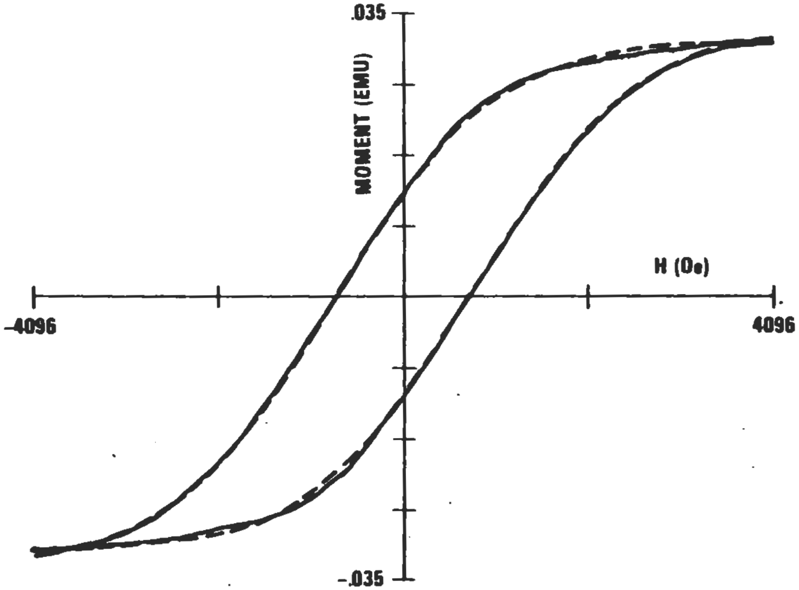
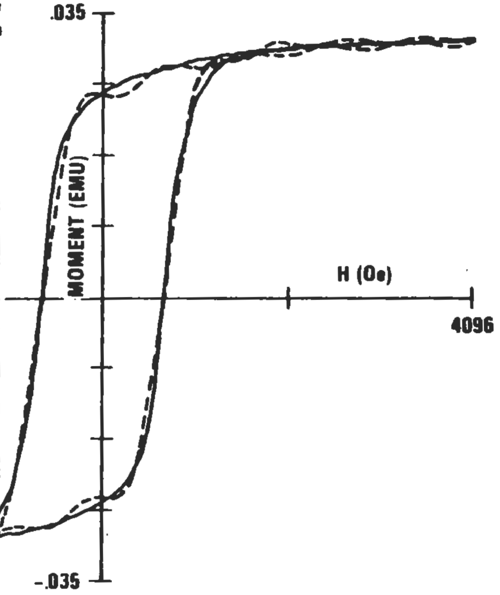


Figure 7. Perpendicular Loop For ISOMAX. Solid Curve Is Data. Dashed Curve Is Fourier Reconstruction.

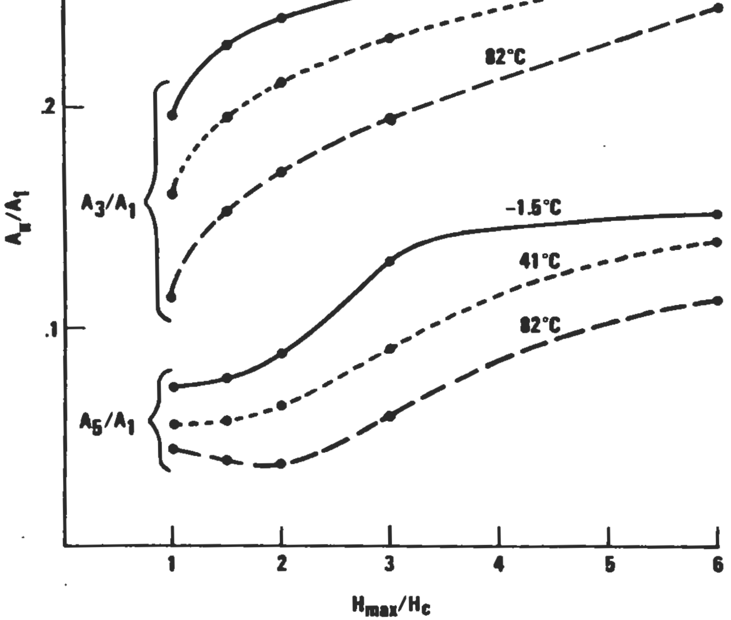
MOMENT (emu)



Phase angles shown are the same as the corresponding values in Fig. 3(b) to within factors of 360°.

n	A_n (in units of m_s)	ϕ_n (°)
1	1.240	347
3	0.350	136
5	0.186	284
7	0.120	71.6
9	0.082	220
11	0.060	9.7
13	0.045	159
15	0.034	310
17	0.027	101
19	0.020	253

Figure 8. Ampex 721 Loop With $(H_{max}/H_c) \approx 6$. Solid Curve is Data. Dashed Curve Is Fourier Reconstruction.



T (°C)	m_s (x10⁻² emu)	S	H_c (Oe)
-1.5	3.61	0.83	1132
41	3.42	0.78	574
82	3.15	0.69	307

Figure 6. Temperature Influence On H_{max} Dependence of A_3/A_1 and A_5/A_1 For ISOMAX.