A SAMPLING WINDOW TEST METHOD FOR EVALUATION OF PHASE ENCODED RECORDER SYSTEMS

J. P. LERMA and C. A. LINDQUIST
Odetics, Inc.
Anaheim, California

Summary. Self-clocking, digital phase encoded data formats have gained popular acceptance in the field of high density digital magnetic recording. At high transition densities, random noise processes can play a prominent role in determining system performance and reliability.

The eye pattern technique of assessing the relative merit of a signal with respect to noise is severely limited at high transition densities. The stringent requirements associated with high density recording and the limitations of eye pattern analysis have stimulated the development of a digitally implemented sampling window analyzer which permits the direct evaluation of the statistical properties of a digital phase encoded reproduce waveform.

The analyzer observes data transitions through two time sampling windows for the purpose of estimating pattern independent conditional probability. The statistical parameters of the conditional probability obtained can be used to detect latent sources of noise and to define optimum record zone parameters.

Introduction. Digital magnetic tape recorders commonly encode data to be recorded in a format in which the spectral content of the encoded signal contains little or no DC in an effort to overcome the limited low frequency response of the reproduce process. Codes such as bi-phase and delay modulation satisfy this requirement and, in addition, provide a self-clocking feature.

The bandwidth required by bi-phase generally restricts its use to relatively low packing densities. Delay modulation, in contrast to bi-phase, is bandwidth conserving permitting recorded bit packing densities approximately double that of bi-phase. A representative delay modulation waveform and the encoding rules are illustrated in Figure 1. The increased packing density afforded by delay modulation is, however, not realized without penalty. At high packing densities, the percentage allowable jitter between successive transitions is reduced in direct proportion to the increase in packing density. In addition, delay modulation generates a finite DC component. Since the DC component cannot be reproduced, wandering baseline effects significantly affect the reproduce signal. Because of these factors, delay modulation is generally less tolerant of noise and distortion than is bi-phase at a comparable transition density.

When high density delay modulation data is reproduced, the resulting waveform contains a band limited signal component plus noise due to sources such as uncompensated phase shifts, non-linear response, crosstalk and high frequency tape vibrations. The relative merit of the composite signal is often assessed by observation of the so called eye pattern, obtained by displaying on an oscilloscope superposed bits of an encoded random word.

The eye pattern oscilloscope photograph of Figure 3 was obtained from a high density spaceborne recorder employing delay modulation. Band limiting limits the slope of the signal and may introduce jitter due to intersymbol interference which, together with noise, tends to smear the zero crossings along the time axis. The clear areas overlaying the baseline represent the available signal margin with respect to the decision boundaries.

The eye pattern in effect displays the result of a stochastic process in which the intensity of the eye pattern image as a function time is proportional to the probability of occurrence of transitions. The usefulness of the eye pattern, however, is severely limited by the ability of the human eye to distinguish contrast.

The stringent requirements associated with the high density recording of delay modulation encoded data and the limitations of eye pattern analysis have stimulated the development of a digitally implemented sampling window analyzer analogous to a high resolution, infinite contrast eye pattern which permits the direct evaluation of the statistical properties of the reproduced waveform.

Though the analyzer was developed to fulfill a specific need with respect to delay modulation, the device may be applied generally to any digital phase encoded data format or guaranteed transition NRZ code.

Theory of Operation. The analyzer is based on certain observations regarding the delay modulation format; however, similar conclusions can be drawn regarding any digital phase encoding scheme.

From the waveform illustrated in Figure 1, it is clear that the encoded binary information in delay modulation is represented in terms of the delay time between transitions of the signal. There are three such discrete delays which may be denoted by T_i, i = 1, 2, 3. The probability of a transition after a delay of t is given by:

$$P(t) = \begin{cases} 0 & t \neq T_i \\ P(T_i) & t = T_i \end{cases}$$

The reproduce process, however, adds a random component to the signal which tends to smear the occurrence of transitions about each T_i. Each T_i thus gives rise to a set, $N(T_i)$, of possible values of t at which a transition may occur. A continuous probability density function f(t) is thus formed, conditionally dependent on the occurrence of T_i:

$$f(t) = \sum_{i=1}^{3} f\left[t \mid t \in N(T_i)\right] P(T_i) \qquad (1)$$

Because $P(T_i)$ is dependent on the encoded binary data, f(t) is pattern dependent. What is, in fact, of greater interest in assessing the effects of noise on the reproduce process, is the pattern independent conditional probability contained in the summation of (1). Solving (1) for this quantity, the following relation is obtained:

$$f\left[t \mid t \in N(T_i)\right] = \frac{f(t) - \sum_{j=1,\ i \neq j}^{3} f\left[t \mid t \in N(T_j)\right] P(T_j)}{P(T_i)} \qquad (2)$$

The summation on the right side of (2) represents the possible occurrence of t due to T_j where $i \neq j$. At low error rates, the contribution of this term may be considered negligible such that (2) may be expressed simply as:

$$f\left[t \mid t \in N(T_i)\right] = \frac{f(t)}{P(T_i)} \qquad (3)$$

Since by definition $f(t = T) = 0$, of practical interest is the probability $P[(T < t < T + \Delta T) \mid t \in N(T_i)]$ which can be obtained from (3) by integration, considering $P(T_i)$ as a constant.

$$P\left[(T < t < T + \Delta T) \mid t \in N(T_i)\right] = \frac{P(T < t < T + \Delta T)}{P(T_i)} \qquad (4)$$

The sampling window analyzer, in effect, forms this ratio in terms of relative frequency of occurrence. A Block Diagram of the analyzer is illustrated in Figure 2. Master timing is provided by a high frequency clock generator operating at N times the data rate. The N-times clock defines the basic sample interval of the analyzer as T_b/N, where T_b is the nominal bit interval. Asynchronous transitions of the input data are synchronized to the N-times clock by the transition detector. The pulse output of the transition detector is applied to two variable delay pulse generators, A and B, such that each transition gives rise to two sample pulses, A and B. The sample period spanned by pulse A is defined by the interval K_a T_b/N, $(K_a + 1)$ T_b/N, where K_a is the integral delay setting of sample pulse A. Similarly, the sample period spanned by pulse B is defined by K_b T_b/N, $(K_b + D)$ T_b/N, where K_b is the integral delay setting of pulse B and D is an integer related to the width of the pulse. Both pulse A and pulse B are individually gated with the output of the transition detector. The respective outputs of these gates are then applied to the A and B inputs of an A divide by B counter.

To determine the significance of the ratio indicated by the counter, it is convenient to denote the number of sample pulses generated per unit time by M and the number of detected transitions gated by the sample pulse per unit time as M (a, b) where a, b defines the interval spanned by the pulse, The ratio, R, may then be expressed:

$$R = \frac{M \left[K_a \; T_b/N, \; (K_a + 1) \; T_b/N\right] /M}{M \left[K_b \; T_b/N, \; (K_b + D) \; T_b/N\right] /M} \tag{5}$$

Interpreting relative frequency of occurrence as probability and substituting into (5):

$$R = \frac{P\left[K_a \; T_b/N < t < (K_a + 1) \; T_b/N\right]}{P\left[K_b \; T_b/N < t < (K_b + D) \; T_b/N\right]} \tag{6}$$

Choosing K_a/N such that:

$$K_a \; T_b/N = T$$

$$(K_a + 1) \; T_b/N = T + \Delta T$$

$$P\left[K_a \; T_b/N < t < (K_a + 1) \; T_b/N\right] = P\left(T < t < T + \Delta T\right)$$

Choosing K_b and D such that:

$$(D - K_b) \; T_b/N \geq t \text{ for all } t \; \varepsilon \; N \; (T_i)$$

$$P\left[K_b \; T_b/N < t < (K_b + D) \; T_b/N\right] = P(T_i)$$

Substituting into (6):

$$R = \frac{P \; (T < t < T + \Delta T)}{P(T_i)}$$

Which is the relation expressed in (4) thus:

$$R = P\left[(T < t < T + \Delta T) \mid t \in N(T_i)\right]$$

Applications. A Schottky T^2L version of the analyzer has been fabricated and successfully used on a number of advanced systems manufactured by Odetics, Inc. for use in satellite applications. The reliability requirements and acceptance level testing associated with such recorder systems demand the strictest definition and control of the record zone with regard to such variables as bias, write current and phase compensation. These variables may be easily optimized using the analyzer.

In its present configuration, the number of sample intervals, N, is limited to 24. While it would be desirable to have a larger number of sample intervals, N = 24 has proven sufficient to resolve the pertinent statistical parameters of signals reflecting reproduce rates in excess of 500 Kb/s derived from recorded bit packing densities of 13 Kb/in.

Figures 3, 4 and 5 illustrate the single track reproduce signature of a high density, five track interleaved, high data rate recorder typical of those to which the analyzer has been applied. The per track reproduce bit rate is 546 Kb/s derived from a bit packing density of approximately 13 Kb/in. Figures 3 (a) and 3 (b) reflect the effects of an excessive bias condition. Figures 4 (a) and 4 (b) reflect an optimum bias condition. There is little, if any, difference between the eye patterns corresponding to the stated conditions. Moreover, the measured error rates of the two recordings over the entire tape length differed by a negligible amount. Yet, the excessive bias condition is clearly reflected in the spread of the sampling window plots for $N(T_i)$ and the calculated standard deviations σ of each $N(T_i)$. Should such a condition remain undetected, it is probable that the toll exacted by normal parameter drifts with time may severely limit the useful life of such a recorder in space.

Other recorder parameters such as compensation for peak shift phenomena and wandering baseline effects can be assessed using the sampling window analyzer. Figure 5 (a) depicts the eye pattern obtained when attempting to reproduce a 32 bit sequence containing a significant DC component. Figure 5 (b) is the corresponding sampling window plot. (Note that the absence of T_2) causes $N(T_2) = \emptyset$, the empty set, thus $P\,[t \mid t \in N(T_2)] = 0$.) The wandering baseline effect is clearly reflected in the spread of the sampling window plot for $N(T_3)$.

Conclusions. Digital magnetic recording systems frequently employ digital phase encoded data formats in an effort to overcome a lack of low frequency response. At high packing densities, however, random noise components in the reproduce waveform may severely affect recorder performance.

The resolution afforded by eye pattern analysis of the reproduce waveform is highly dependent on the ability of the human eye to distinguish contrast. The sampling window analyzer was thus developed to permit high resolution statistical analysis of the reproduce waveform.

The sampling window analyzer has been shown to measure pattern independent conditional probability. The conditional probability data obtained may be plotted and interpreted as an approximation to the density function of the noise process. The analyzer has proven to be of value in detecting latent reducible noise occurring as a result of inadequate definition of record zone parameters.

The resolution of the analyzer in its present configuration has proven adequate at data rates in excess of 500 Kb/s. Future speed requirements, however, may necessitate an analyzer design utilizing non-saturable logic elements which will permit operation at per track bit rates up to 4 Mb/s.

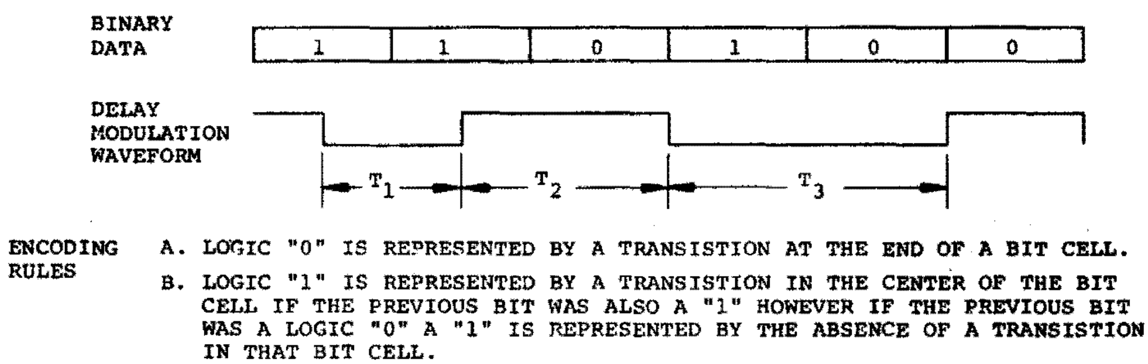


FIG. 1 DELAY MODULATION

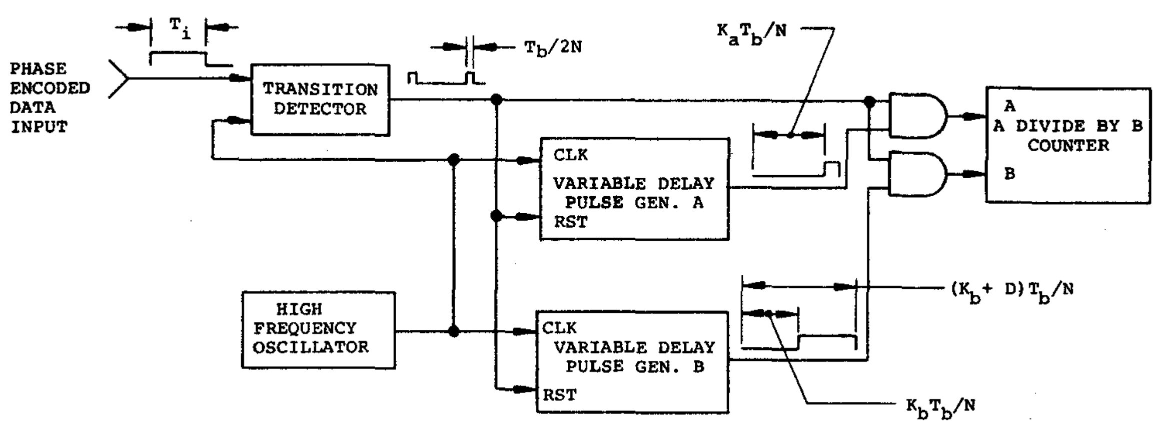


FIG. 2. SAMPLING WINDOW ANALYZER BLOCK DIAGRAM

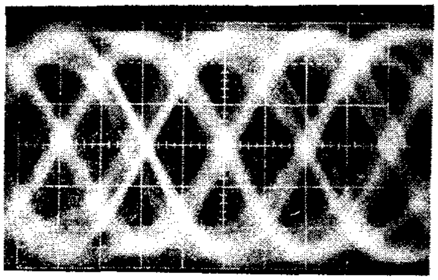
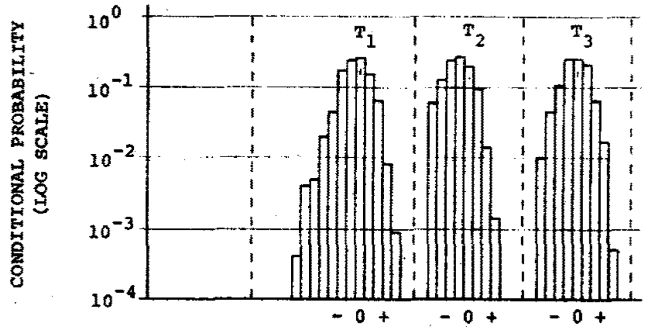


FIG (3)a.

FIG (3)a. EYE PATTERN OF HIGH DENSITY DELAY MODULATION RECORDER WITH EXCESSIVE BIAS.
FIG (3)b. SAMPLING WINDOW ANALYZER PLOT OF SAME CONDITION.



NORMALIZED $N(T_i)$
(NORMAL SCALE)
FIG (3)b.

STD DEV.

T_1	T_2	T_3
1.57	1.73	1.39

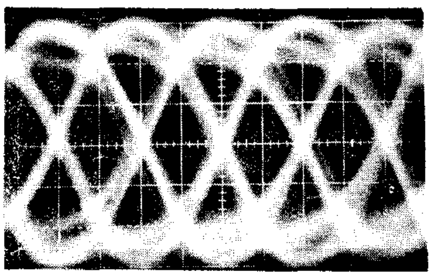
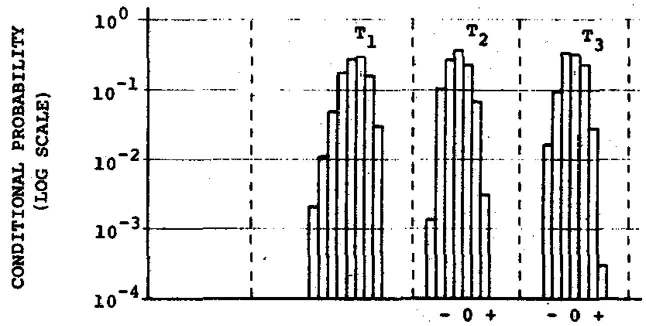


FIG (4)a.

FIG (4)a. EYE PATTERN OF RECORDER WITH OPTIMUM BIAS.
FIG (4)b. SAMPLING WINDOW ANALYZER PLOT OF SAME CONDITION.



NORMALIZED $N(T_i)$
(NORMAL SCALE)
FIG (4)b.

STD DEV.

T_1	T_2	T_3
1.36	1.54	1.08

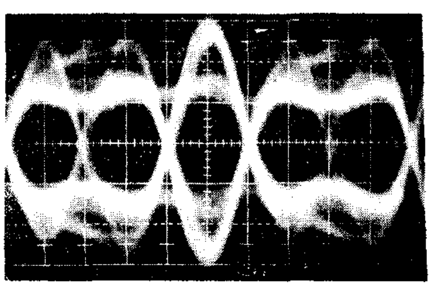
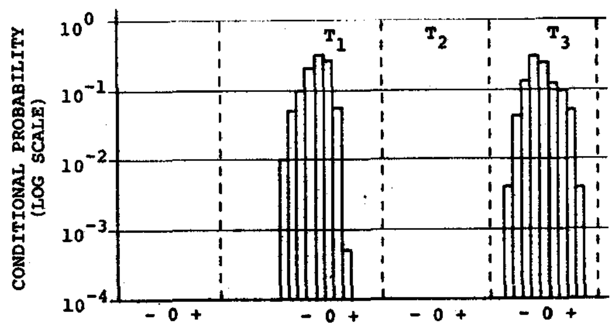


FIG (5)a.

FIG (5)a. EYE PATTERN OF 32 BIT SEQUENCE WITH SIGNIFICANT DC COMPONENT.
FIG (5)b. SAMPLING WINDOW PLOT OF SAME CONDITION



NORMALIZED $N(T_i)$
(NORMAL SCALE)
FIG (5)b.

STD DEV.

T_1	T_2	T_3
1.78	N/A	1.51