R. A. Skov

Pulse Time Displacement in High-Density Magnetic Tape

Abstract: In computer magnetic tape systems, a primary factor in character rate is recording density. Pulse time displacement places a direct limit on the maximum bit density which may be used in parallel NRZI recording systems in which recovery of the information on readback depends on correct synchronism of all tracks. Measurement techniques for evaluation and analysis of pulse time displacement are described. A sawtooth oscilloscope display is particularly useful for observing time displacement as a function of time. The various components of time displacement and their causes, such as skew and pulse crowding, and methods used to reduce them are discussed. This study led to the adoption of a recording density exceeding 500 bits per inch for the IBM 729-III Magnetic Tape Unit.

Introduction

The speed at which information is transferred to and from magnetic tape storage is an important factor in the efficiency of large-scale digital computer applications. In the IBM 727-III Magnetic Tape Unit, the maximum realizable information rate is limited by the degree of synchronization of the several tape tracks during recording and readback.

In this tape system, the writing of digital information is serial by character and parallel by bit with the NRZI recording method.* Although for a given character the writing of the bits (binary "ones") in each track is initiated by the same timing pulse, during readback they are not sensed at exactly the same time. This phenomenon may be called "intertrack pulse time displacement," or merely "time displacement."

For correct reading by the self-synchronization of characters, the period between characters must be at least twice the time displacement within a character. Density is inversely proportional to the product of the period and the physical tape speed. If the time displacement of the pulses or bits is reduced, the density of recorded information, and thus the speed of tape operation, can be increased.

The purpose of this investigation is to analyze the nature and causes of pulse time displacement and to find means of minimizing it. The emphasis is on a practical solution of the problem, and the basic IBM 727-III tape transport, modified to operate at 112.5 inches per second, is used in this study. Figure 1 shows the basic arrangement of the parts which guide and drive the tape.

Two approaches to the problem of time displacement have been used. The first was to read tape under marginal timing conditions for different system parameters and to compare performance on the basis of bit recovery. The second approach was direct measurement of time displacement by various techniques. This paper will first describe the measuring techniques and will then discuss the components of time displacement.

*A non-return-to-zero method in which a change of flux is involved in writing each "one" bit and no change of flux for writing a "zero."

Measurement techniques

- *Testing for information loss vs. character gate*

A basic method of evaluating intertrack time displacement is to find the minimum character gate at which a large file of characters may be read correctly. Figure 2 illustrates the character-gate logic used in this investigation. Sensing of a pulse in any track turns on its first register; all first-register outputs are connected to a common OR circuit to produce a first bit line. The first bit of a character being read initiates a character gate of adjustable duration. Subsequent pulses which turn on their first register positions before the character gate is turned off are accepted as part of the same character. When the character gate falls, the first register is turned off and the character transferred to the second registers. The character is then checked for correctness bit by bit, and if the character is in error, a "one" is added to an error counter. If the time displacement from the first bit to another bit of the same character exceeds the time interval from the first bit to the fall of the character gate, the latter bit will be missing from the character. The same basic character-gate logic (excluding the checking) is used in current tape systems, with the nominal character-gate timing equal to half the period.* It is the most efficient method of recovering information, because in its basic form only one time delay is required, no timing marks or bits are used, and only one character of buffering is necessary.

The minimum error-free character gate varies from run to run because of randomness of tape skew and other effects. Also, occasional errors may not be representative of the conditions being tested. The method is therefore extended to that of plotting the average number of errors vs. character gate for several runs, using character gates which are at the fringe of the error region. Such plots are then compared to determine the degree of improvement, if any, effected by controlled changes in the tape system.

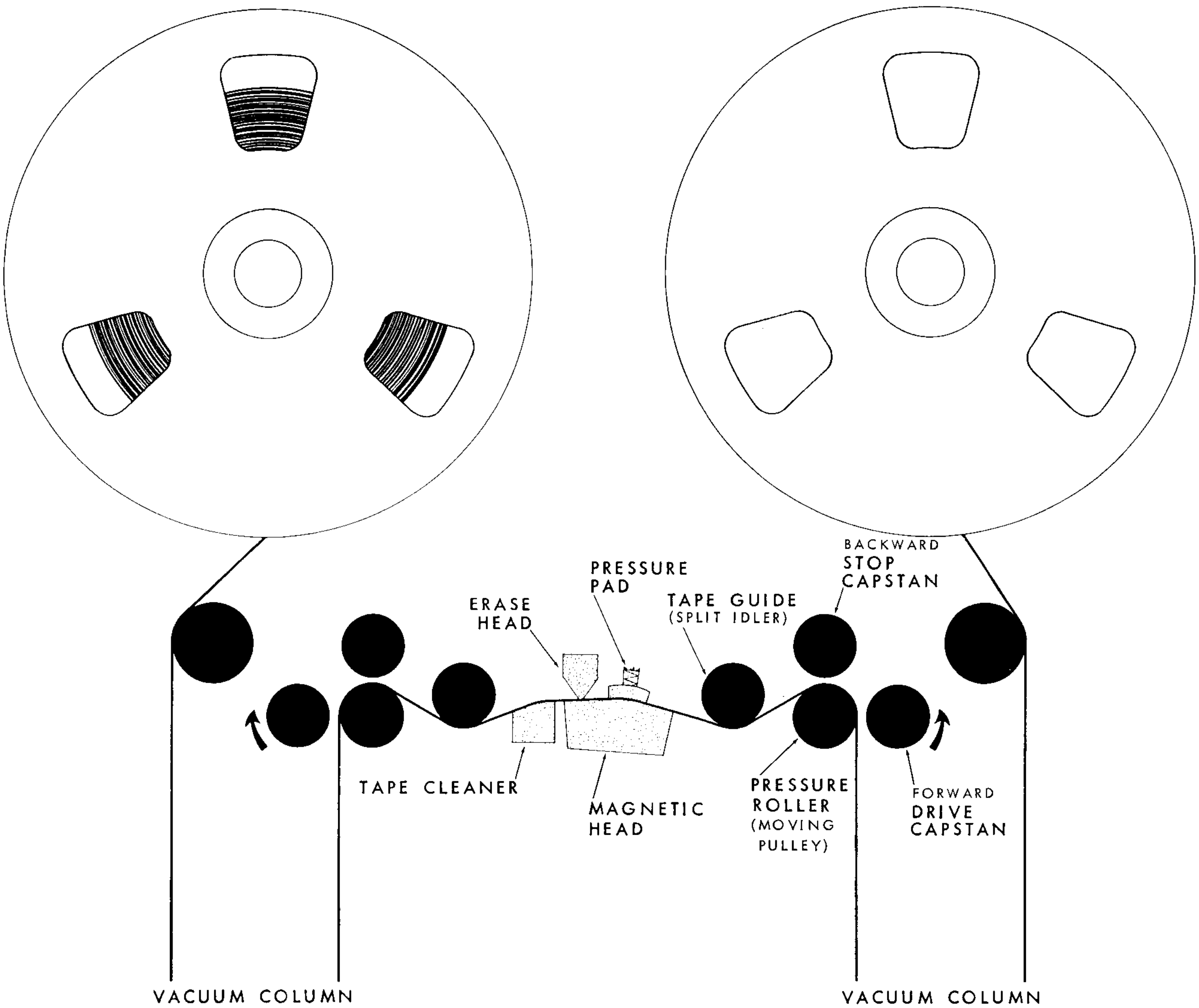
This method is the final measure of the over-all performance, but it is very time-consuming and does not yield a direct analysis of the components and sources of time displacement.

- *Microsecond counter*

A commercial electronic counter may be used to count the time interval between two pulses, one of which is wired to its "start" input and the other to its "stop" input. The total character time displacement may be measured by starting the counter on the first bit and stopping it by a signal which signifies that all bits of a character have been received. The counter may also be wired to measure the time displacement between any two tracks or the period between successive pulses in the same track, using

*For derivation of optimum character gate timing as a function of period speed variation and reset or sample time, see Appendix.

Figure 1 **Basic diagram showing path of tape through the IBM 727-III Magnetic Tape Unit.**



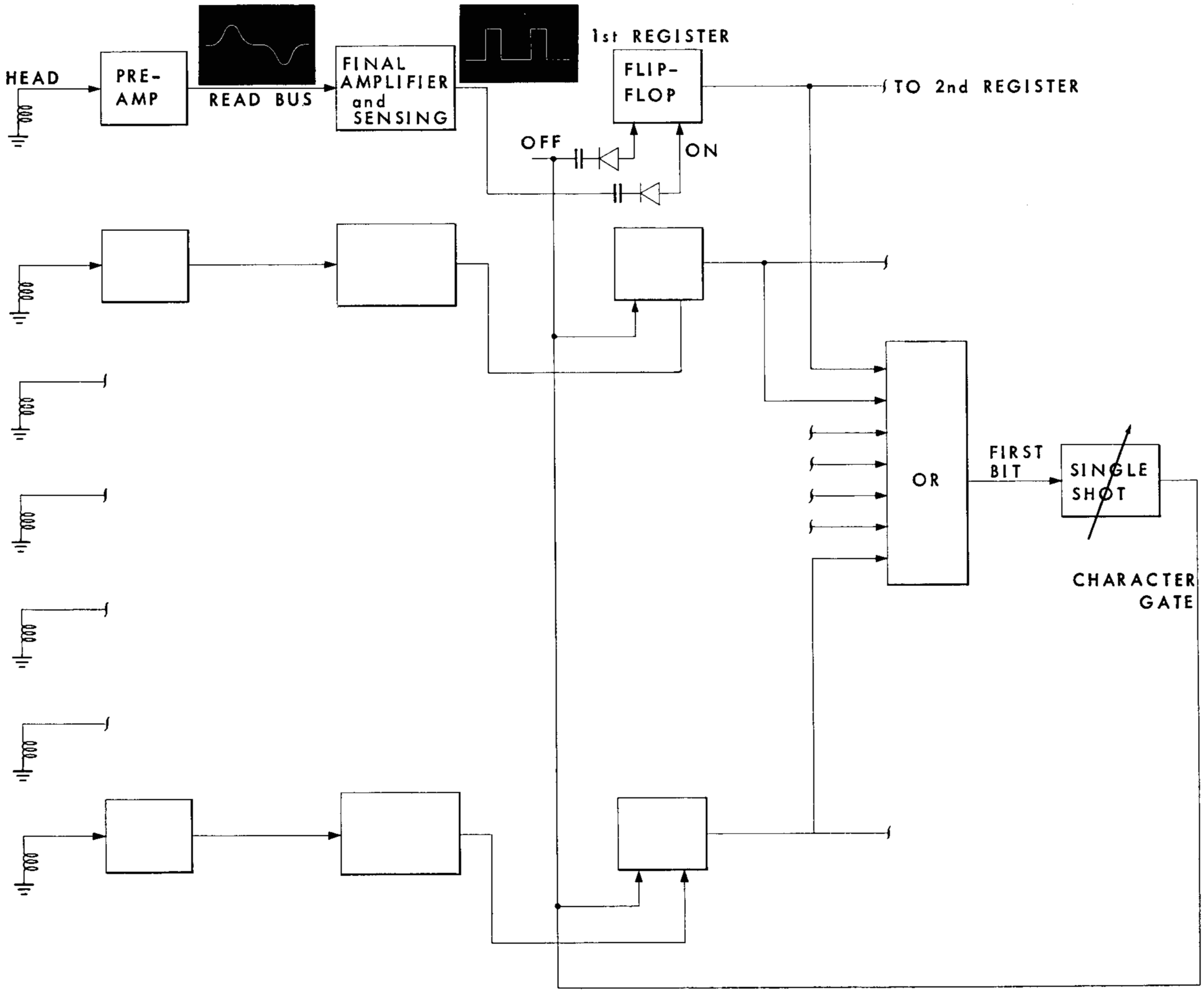


Figure 2 **General form of character-gate logic.**

the signal from the "read" bus or the first register. Since visually reading the counter and plotting results is time-consuming for a significant sample, and since adequate mechanization of the process is not economical, this method was used only to a limited extent.

- *Normal oscilloscope display*

The simplest method of directly observing time displacement is to display on the oscilloscope the first-register output of a given track while triggering the sweep on a reference track. Normally the oscilloscope is synchronized by the leading track or the first bit with sweep speeds on the order of 1 μsec/cm. Successive traces are superimposed. Figure 3 illustrates the display of a leading track, a lagging track, the first bit line and the character gate. The average magnitude and total range of variation of time displacement may be roughly determined on the display. Also, the magnitude of very-low-frequency components of time-displacement error can be seen.

- *Sawtooth oscilloscope display*

This method was developed to permit analysis of higher frequency variations in time displacement in order to identify and eliminate the source of variation. Successive time displacements may be observed as a function of time if they are converted to voltage amplitudes and displayed on the oscilloscope, as sketched in Fig. 4. This conversion is accomplished by the circuit of Fig. 5. The output of the first register controls an RC network which develops a sawtooth pulse having an amplitude proportional to the length of time the first register is "on." The circuit parameters are chosen to produce a sawtooth pulse with linear slope and fast recovery.

Figure 4 illustrates the sawtooth output at different sweep speeds for two tracks, one of which consistently leads the other, in relationship to their normal first-register outputs. The vertical time scale for the sawtooth output is derived directly from its slope, measured at a fast sweep speed. Note that the time displacement represented by a voltage, K(T.D.)* is not the amplitude of the envelope, but the difference between the latter and the reference amplitude, KTa.† In practice, the measurement of most interest is often the peak-to-peak time displacement designated by β in the diagram.

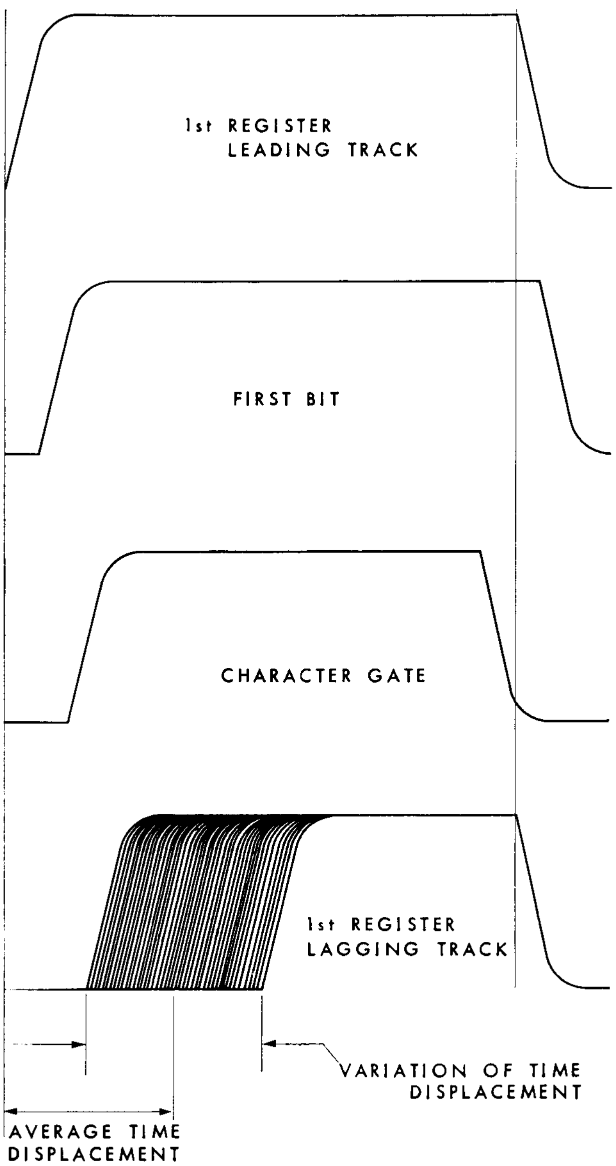
The sawtooth technique is also used to display the varying components of time-displacement error (period variation) between bits of the same track. At mechanical frequencies, this variation is known as "flutter." These components can be displayed with the least modification by reading one track at a time so that it has control of the character gate. Either the inverted first register output or the inverted character-gate output may be connected to an RC network as previously described. Figure 6 shows that the sawtooth amplitude, X, is proportional to the period P minus a constant C.

Another means of displaying time-displacement error is to connect the normal output of the character gate or first register to a negatively returned RC network with the control-diode polarity reversed. The result is the same except that the sawtooth is inverted. A second track can be displayed simultaneously on a dual-trace oscilloscope by disconnecting it from the network of the first bit line and connecting it to a separate delay device, from which the output is applied to a sawtooth circuit.

*T.D. = time displacement.

†A sawtooth pulse whose amplitude is itself proportional to time displacement may be obtained by feeding the result of the first bit line, along with the inverted first register output, to an AND circuit and from there to the RC network. This method would not be suitable for use with coded information, however, since zeros would result in large, false pulses.

Figure 3 **Time displacement in the first register lagging track in time relation to other waveforms.**



Time displacement at mechanical frequencies

- *Drift*

Changes in time displacement at rates below one cycle per second may be referred to as "drift." Before average time displacement can be ascertained reliably, drift must be minimized. Although there is some long-term drift due to unequal "write" current amplitudes and amplifier gains, these are corrected by periodic inspection. Skew is the major cause of drift. In this paper, skew has been defined as the change in azimuth as the tape passes the sensing head.* The drift in time displacement due to skew is naturally greatest between outside tracks. This drift can be easily observed with the normal oscilloscope display, as a slow change in average displacement, Fig. 3. It may be possible to compensate for drift by sensing the position of the reference edge of the tape and feeding back a correction signal to modify the head alignment. The physical displacements involved, however, are quite small. Although several self-correcting schemes conceivably could be used for different phases of time displacement, the general approach here is first to eliminate as much time displacement as possible at the source.

Drift is partly due to the tape itself inasmuch as slight dimensional variations will occur. The front or reference edge of the tape does not always maintain contact with the fixed edge of the guides, a condition which cannot be attributed to maladjustment of the tape guiding mechanism. Limiting the movement of the spring-loaded portion of the guides to the maximum tape width thus limits the total skew. But tape of less than maximum width cannot be rigidly restrained and thus can be skewed to the positive limit of the spring-loaded guide, if a force tends to move the tape in that direction. Such a force is sometimes transmitted to the tape by the pressure rollers.

When tape is driven forward, the left pressure roller (whose function is to operate against forward stop capstan and the backward drive capstan) serves as an idler which is driven by the tape. Any slight misalignment of the roller will tend to move the tape laterally. Figure 7

*The term "skew" or "effective skew" has also been used loosely to mean intertrack time displacement, or any of its causes or components.

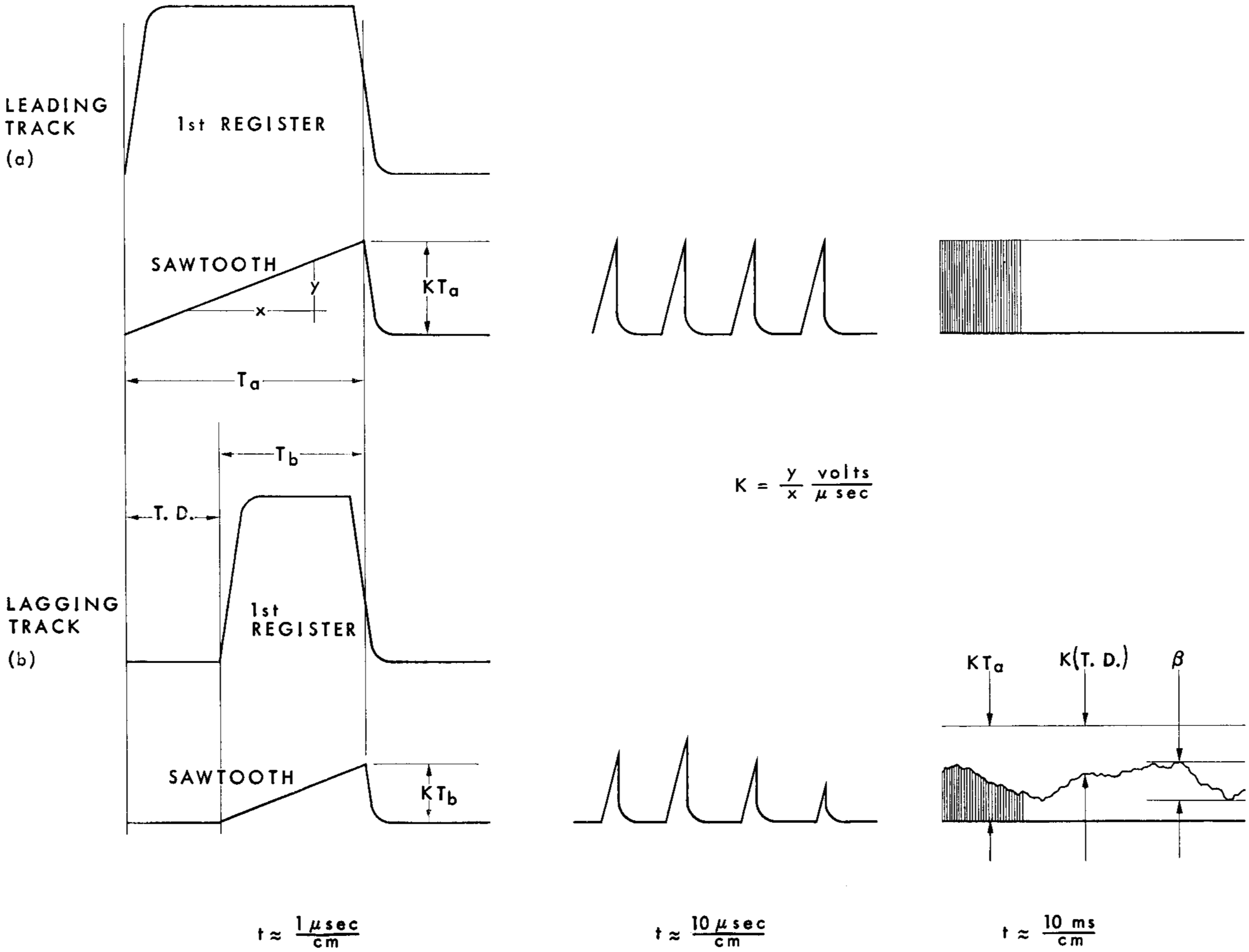
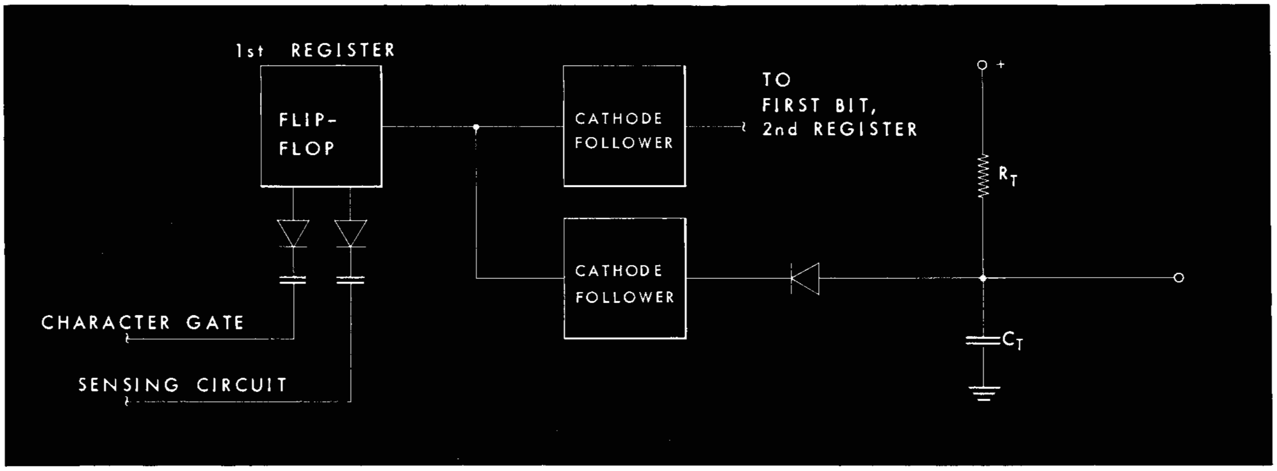


Figure 4 **Sawtooth waveforms at various sweep speeds.**

Figure 5 **Sawtooth display circuit for converting time displacement to voltage amplitudes.**



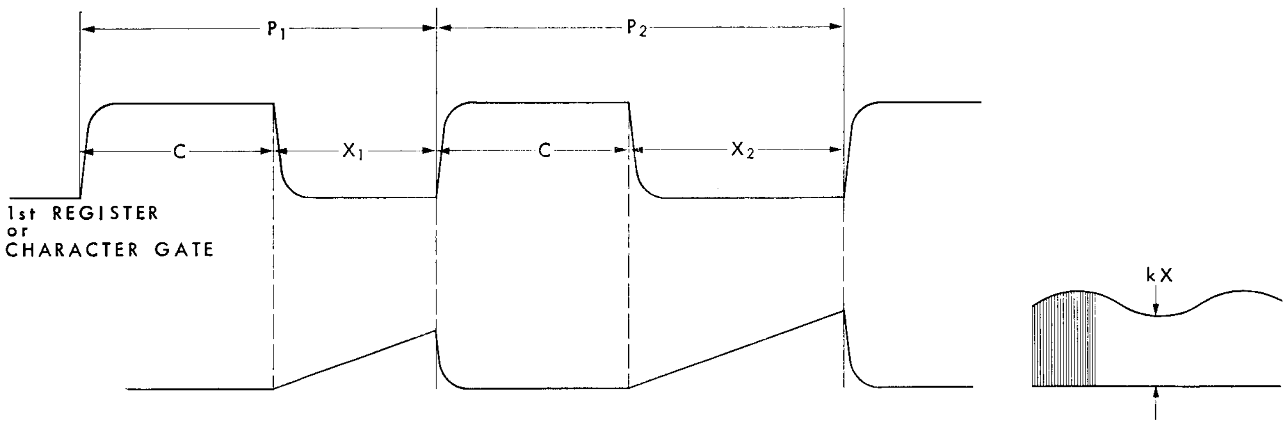


Figure 6 **Relation of sawtooth amplitude to the period between bits in the same track.**

shows an idling roller with an exaggerated misalignment. Arrow (a) is the direction in which the tape will tend to move because of roller friction. Arrow (b) is the lateral component of motion which will exert a force on the guide at (c).

Adopting finer tolerances, however, does not appear to be the most practical method of obtaining better tape alignment from this mechanism. Another approach is the use of air lubrication. An air film is created by blowing air through fine radial holes in the roller by means of a slot in the shaft, which conforms to the portion of the roller over which the tape is wrapped. With such air lubrication, the lateral frictional force is removed and this source of skew is reduced, as explained further in the section entitled "Cyclical Time Displacement."

- *Average time displacement*

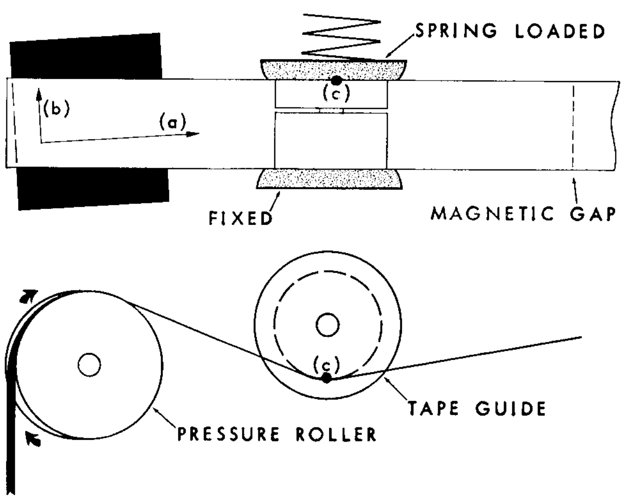
The first prerequisite for tape intechangeability between different tape units is alignment of the magnetic head perpendicular to the direction of tape motion. Final adjustment of the head azimuth is made to produce zero average time displacement between the outside tracks while a master tape is read. This has been the standard practice and is satisfactory for lower recording densities, but still leaves a net average time displacement on the remaining tracks, primarily because of mechanical tolerances and differences in magnetic and electrical characteristics associated with each track. For this reason adjustable delay lines were added to the "read" circuits of each track to compensate for its fixed components of time displacement. In this procedure, the delays were adjusted while reading a master tape which has as nearly ideal recording as possible in all tracks. A similar application has been described by Olson, et al.*

Similarly, a fixed component of time displacement occurs on the tape during the writing operation. The two-gap head makes it practical to compensate for this time displacement, and adjustable delays have been inserted in the "write" circuits for each track. After the "read" head has been compensated against the master tape, the "write" delays are adjusted during the simultaneous read-write operation until zero average time displacement is read between all tracks. Theoretically, the unit will then produce a tape equivalent to the master tape.

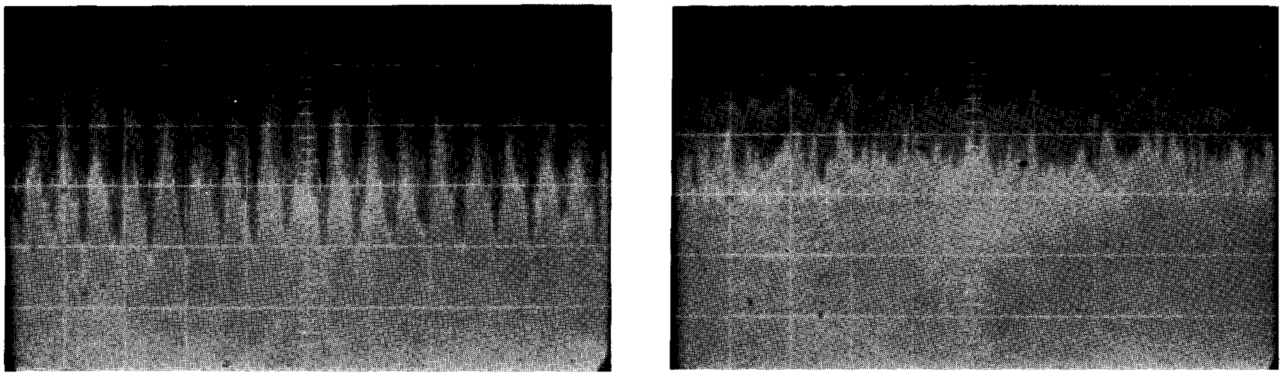
- *Cyclical time displacement*

The higher rates of time displacement cannot be distinguished by means of the normal oscilloscope display. The sawtooth display is used with sweep speeds on the order of 50 msec/cm. Pictures show very complex waveforms because many frequencies are involved. Asynchronous superposition of the skew components, which occurred during writing, upon those which occur during reading adds to the complexity of the skew envelope. However, the frequency of 36 cps stands out most promi-

Figure 7 **Effect of misaligned pressure roller on tape movement.**



*H. F. Olson, et al., "A Magnetic Tape System for Recording and Reproducing Standard FCC Color Television Signals," *RCA Review* **17**, 330-392 (September 1956).



a) Normal transport, split idlers rotating. *b) Same transport with locked split idlers.*

Figure 8 **Oscillograms of time-displacement sawtooth waveforms. Scale: horizontal, 50 msec/cm; vertical, about 1.0 μsec/cm.**

nently for the tape transport analyzed. This frequency is the revolution rate of the tape guides (split idlers). After the tape guides were prevented from rotating, the 36 cps component was eliminated, and thus the peak-to-peak time displacement was reduced. Figure 8 shows an oscilloscope trace of the sawtooth waveform before and after the split idlers were locked.* Preliminary investigation indicates that a non-rotating guide is feasible from the standpoint of tape wear.

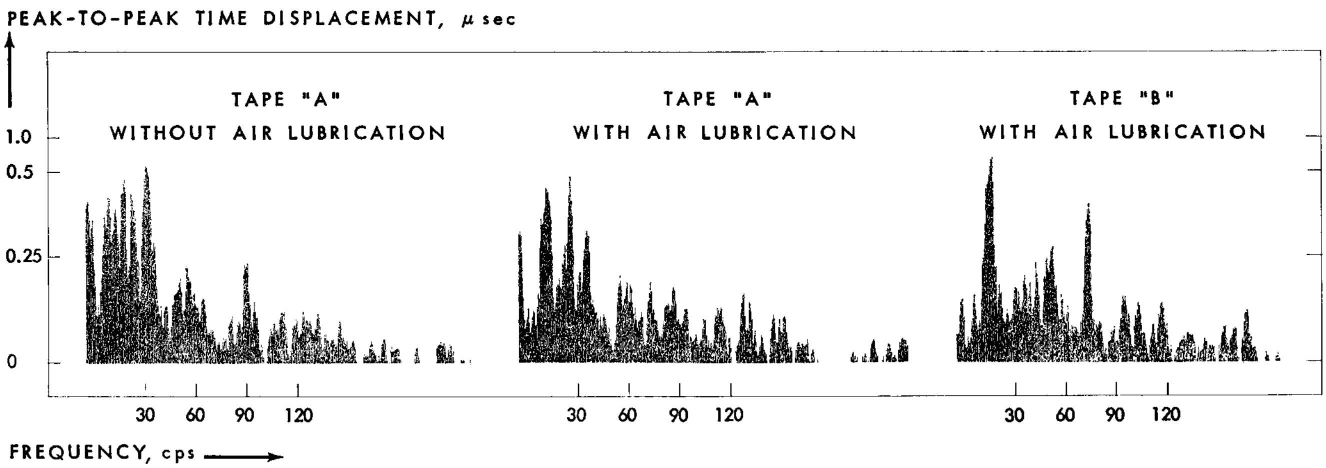
Displaying the time displacement of the middle track and an edge track with respect to the other edge track simultaneously on a dual-beam oscilloscope permits comparison of the phase and magnitude of their frequency components. Such oscillograms show that these cyclical variations are partly due to distortion (shearing) of the tape, as well as to regular skew, the major factor.

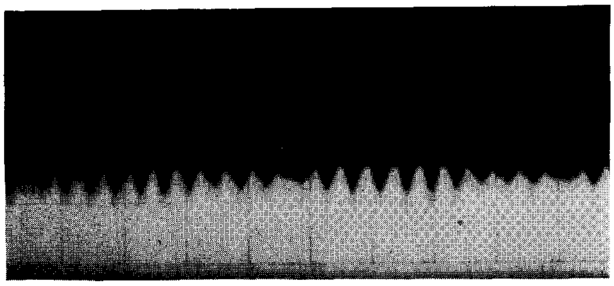
*The dual envelope is caused by asymmetry which is discussed in a subsequent section.

A 30-cycle component of skew is attributed to the pressure rollers and drive capstan, which rotate at 30 cps on the tape transport studied. The air lubrication of the pressure rollers which was previously described, also removes the portion of the 30-cycle component which is caused by the idling roller. Charts of the frequency spectrum of 0.13-sec samples of detected sawtooth waveforms are shown in Fig. 9 under the following conditions: (1) Tape A, without air lubrication; (2) Tape A, with air lubrication; (3) Tape B, with air lubrication. The most prominent and consistent skew component, which is attributed to the width and curvature variations of the tapes themselves, is approximately 13 cps and can be seen in the charts. A similar method of frequency analysis has been described by Frayne and Wolfe* in reference to flutter analysis of sound recording.

*J. Frayne and H. Wolfe, *Sound Recording,* Wiley and Sons, New York, 1949, section 22-8.

Figure 9 **Frequency spectrum analyzer charts showing reduction of 30-cycle component when air lubrication is used for pressure roller in a developmental machine.**





a) Normal tape transport.

b) Same transport with flywheel.

Figure 10 **Oscillograms showing effect of flywheel on flutter. Scale: horizontal, 100 msec/cm; vertical, about 3.5 μsec/cm, equivalent to 14% speed variation per cm. Pulse period: 25 μsec.**

• *Flutter*

Flutter is also important in the character-gate system. For normal speed variations, the maximum realizable recording density, with optimum character gate, is decreased by approximately twice the percentage speed variation, as shown in the derivation in the Appendix. Because the tape is driven by a capstan which is keyed to a synchronous motor shaft, the average speed is considered to be fairly accurate. The only factors which would change average speed are tape slippage and variation of power-line frequency.

With the appropriate sawtooth oscilloscope display, a smooth 30-cps flutter was seen on all tracks, in contrast to the jagged envelope first seen in the skew display. The magnitude of this flutter drifts because the 30-cycle component written on the tape changes in phase relation to the 30-cycle component of flutter which occurs during reading. The phasing is due to slight differences of average speed.

In a series of experiments designed to reduce flutter, the drive capstan was turned down to a more accurate concentricity, but this made no noticeable difference in the flutter. A flywheel was then keyed to the drive capstan motor shaft. This reduced the flutter considerably, as shown in Fig. 10.

Time displacement at recording rates

• *Asymmetry*

A relative time-displacement error between positive and negative pulses is termed "pulse-time asymmetry." This asymmetry can be observed in the sawtooth oscilloscope display of the variation in period for a single track, when continuous bits are recorded. Sweep speeds which display a small number of sawtooth pulses are used in order to relate the asymmetry to the tape signal taken from the "read" bus, as in Fig. 11. Asymmetry also appears, however, as two superimposed envelopes at the slow sweep speeds used for flutter measurement. Asymmetry adds to intertrack time displacement because its magnitude and sense varies between tracks. The sense varies because both positive and negative pulses may be contained in the same character of coded information. Asymmetry also varies with density.

In order to determine how much asymmetry may have been caused by the amplifier and sensing circuits, the head cable was reversed, presenting an inverted signal to the system. A reversal in the normal phase relationship between the "read" bus and the sawtooth showed that most of the asymmetry was present in the signal coming from the head, as shown in Fig. 11.

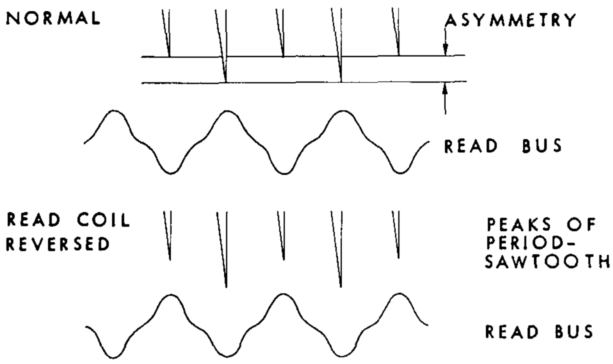
Changing the polarity of the erase head on a single-gap head unit showed that the presence of this dc magnetic field causes considerable asymmetry. Other evidence shows that some asymmetry is caused by a residual magnetism in external and internal parts of the head assembly, and by other external magnetic fields. The time displacement due to asymmetry as well as amplitude asymmetry can be minimized by improved shielding* and by the use of ac erasing where feasible.

• *Pulse crowding*

At higher recording densities, interference between successive bits on tape causes a narrowing of the pulse width,

*In the two-gap head unit, which does not employ an erase head, the previous state of magnetization of the tape influences the asymmetry.

Figure 11 **Pulse-time asymmetry in relation to "read" bus waveform.**



changing its characteristic shape. Excessive pulse crowding also reduces the pulse amplitude. This interference between pulses varies according to the instantaneous density, which will differ between tracks because of coded information. With the currently used sensing scheme in which the time reference of the pulse is its leading edge, this results in a time displacement between tracks, even where the amplitude is constant. The sawtooth oscilloscope display is used to measure this component of time displacement as a function of the sequence of bits. This arrangement consists of writing a repetitive coded group of bits in one track, a continuous series of bits in another track, and a single bit per coded group in a third track. The time displacement between the coded track and the continuous track is displayed while the third track is used to synchronize the oscilloscope. Sawtooth waveforms are shown at the bottom of Fig. 12.

A direct analysis of tape "read" signals under various coding and tape-to-head spacing conditions shows that the peak portion of each "read" signal is most consistent in timing.

A peak senser should be used, therefore, for registering bits at the proper time. However, since a differentiator is used to locate the signal peaks, and is a frequency-sensitive device, two undesirable effects normally occur:

1. Signals containing low-frequency components, such as the reading of isolated "ones" through tape-to-head spaces, are attenuated and tend to be missed by the sensing circuit.
2. There is excessive sensitivity to high-frequency "noise" pulses.

To compensate for these difficulties the system shown in Fig. 12 was developed. The amplifier stages include low-frequency boost networks which tend to flatten out the sensitivity characteristics of the device. Noise clipping is applied at the mixer stage. This eliminates noise on the baseline of the signal waveform to the extent of about 20% of normal signal amplitude. After differentiation, the "read" signal is again amplified, clamped, and applied to a Schmitt trigger through a one-way integrator. This circuit specifies that the signal have a minimum pulse width as well as minimum amplitude in order to turn on the Schmitt trigger. In this manner noise transients which contain frequency components only slightly higher than those of normal signals are effectively blocked.

Conclusion

In the phase of development work on high-speed magnetic tape systems which has been described here, significant components of the variations in pulse time displacement in a tape transport model have been isolated. The techniques described in this paper have shown how most of these sources of variation can be eliminated. First, a simple technique was developed for the analysis of the higher frequency variations in time displacement by means of a sawtooth display on the oscilloscope. Use of this measurement method led to the specific identification of three important components — cyclical skew, pulse-time asymmetry, and pulse crowding — and is proving to be a useful tool for minimizing these components. The cyclical skew and the drift introduced by the pressure roller were effectively reduced by air lubrication. It has also been shown that another cyclical component of skew may be avoided if tape guides are non-rotating. In order to minimize the time displacement due to pulse crowding, a peak-sensing circuit with good noise discrimination has been designed. Flutter has been reduced by means of a flywheel.

One of the important advantages of this approach to the design of a higher-density tape system is continued use of standard half-inch tape. The utilization of these techniques permits use of densities exceeding 500 bits per inch with the efficient character-gate technique employed in the IBM 729-III Magnetic Tape Unit system.

Further development is being done on the devices and techniques described in this paper. The identification of the components of time displacement shown in this investigation has been a fundamental step toward increasing recording density of magnetic tapes to meet the design goals of large-scale digital computers.

Appendix

1. *Derivation of optimum character gate as a function of period, speed variation, and reset time*

The character gate is the timing device which causes the first register to accumulate all the bits belonging to a single character at a time. In Fig. 13, each diagonal line represents a tape character having the greatest tolerable skew or time displacement. Although time displacement within a character is not entirely a linear function of the track location, a character is conveniently represented by a straight line, rather than a band, in an analysis which makes no assumptions on the degree of linearity. Figure 13a shows the geometry of three pairs of adjacent characters written at minimum, nominal and maximum tape speeds. Figure 13b shows the timing for the same three pairs of characters when read at maximum, nominal, and minimum speeds, respectively.

The symbols in Fig. 13 are defined as follows:

Velocity, $v=V(1\pm x)$,

where V = nominal velocity

Speed variation, $x\equiv\frac{\Delta v_{\max}}{V}$

Nominal wavelength, $W=PV$

Minimum wavelength, $U=PV(1-x)$

Maximum wavelength, $Y=PV(1+x)$

d = Character displacement (due to skew): $d_1\approx d_2\approx d_3$

P = Nominal period

$$\text{Minimum period, } N=\frac{PV(1-x)}{V(1+x)}=P\frac{1-x}{1+x} \qquad (1)$$

$$^{*}N\approx P(1-2x)$$

*Approximations for relatively small values of r, x, T_s

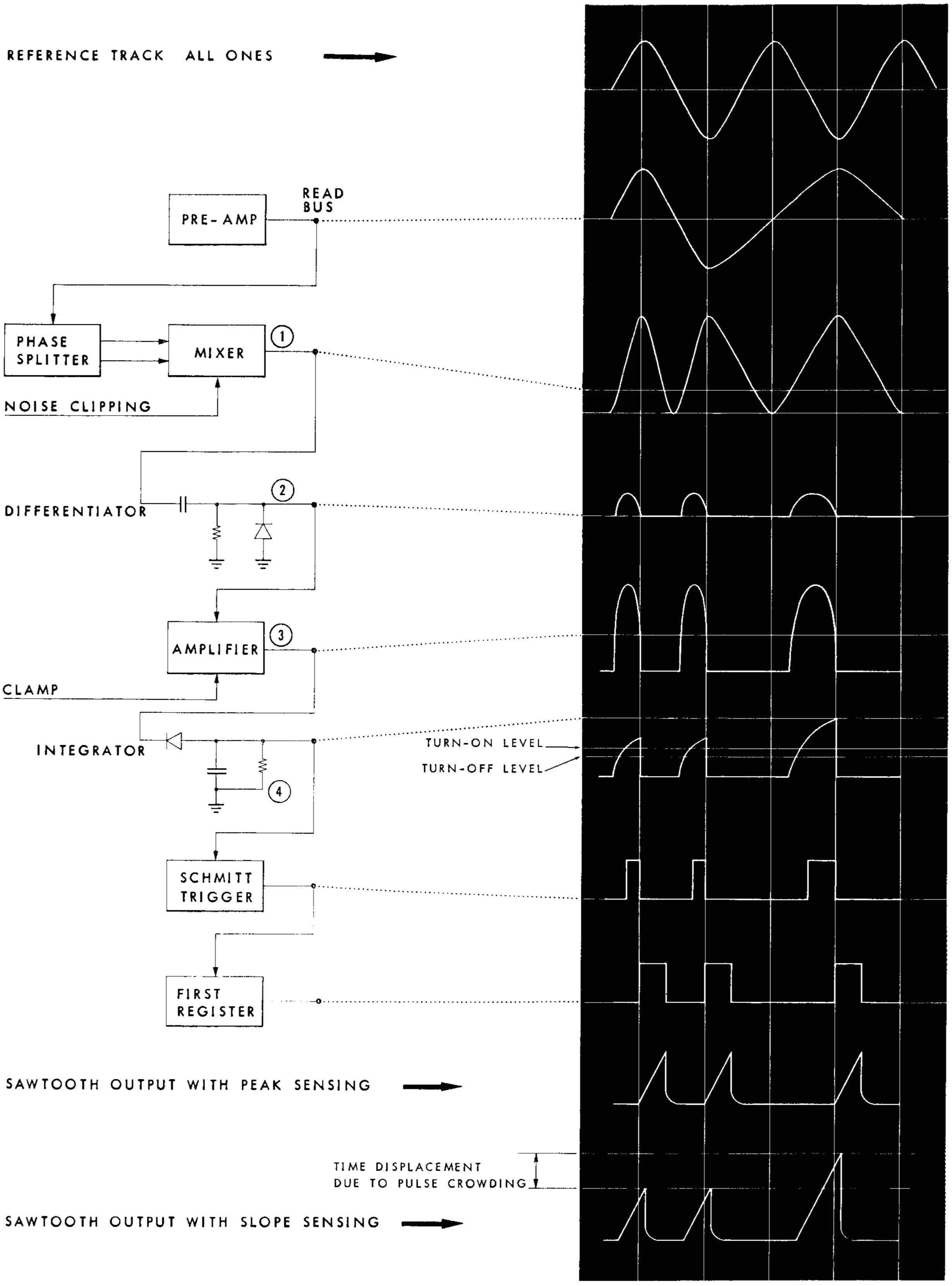
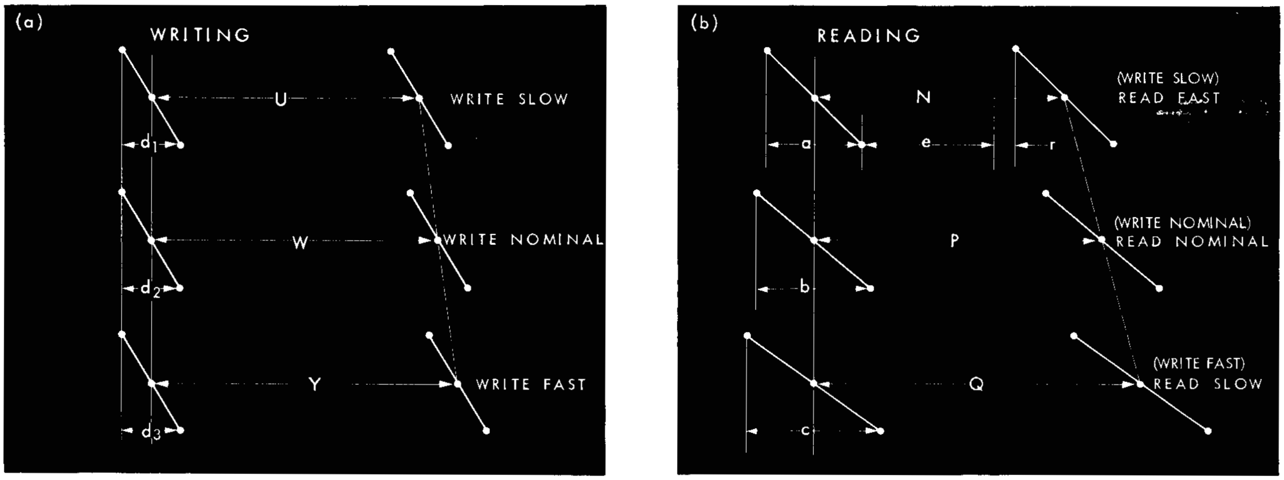


Figure 12 **Peak-sensing circuit for minimizing effects of pulse crowding.**



a) Written at minimum, nominal and maximum tape speeds.

b) Read at maximum, nominal and minimum speeds.

Figure 13 **Geometry and timing for three pairs of adjacent characters.**

Maximum period, $Q = \dfrac{P(1+x)}{1-x} \approx P(1+2x)$*

r = reset, or sampling time.

Symbols a, b, c are the character time displacements for the three cases in Fig. 13b.

Neglecting the very small possible displacement differential due to write-switching phase differences, the character displacements (d_1, d_2, d_3) for the three cases are essentially equal and independent of tape writing speed. During reading, however, character time displacement becomes a function of speed, as the diagram and equations show. The greatest character time displacement, c, occurs when reading speed is slow. It can be shown that $e+r$ (for the case of writing slow and reading fast) as illustrated in Fig. 13b, is the minimum interval between the closest bits of adjacent characters. The symbol r designates the reset or sample time during which bits cannot be distinguished. Since in the basic character-gate system a fixed gate is initiated by the first bit of each character, and since the information coding may cause the first bits to be distributed at random, the character gate must not exceed e and yet must not be less than c or an error will occur. Therefore, the worst case of time displacement which can be tolerated occurs when e equals c, and this is also the optimum character gate, C_g. The optimum character gate is given in Eq. (9).

For optimum character gate,

$$C_g = e = c. \tag{2}$$

But

$$N = a+e+r, \qquad a+e = N-r \tag{3}$$

and

$$a = \frac{2d}{V(1+x)} + T_s = \frac{T_D}{1+x} + T_s \tag{4}$$

where $T_D \equiv \dfrac{2d}{V}$ and T_s = sensing time displacement.

Similarly,

$$c = \frac{T_D}{1-x} + T_s. \tag{5}$$

From (1, 2, 3, 4, 5):

$$\frac{T_D}{1+x} + T_s + \frac{T_D}{1-x} + T_s = P\frac{1-x}{1+x} - r; \tag{6}$$

$$T_D = \frac{P\dfrac{1-x}{1+x} - r - 2T_s}{\dfrac{1}{1+x} + \dfrac{1}{1-x}}. \tag{7}$$

From (2, 5, 7):

$$C_g = c = \frac{P\dfrac{1-x}{1+x} - r - 2T_s}{\dfrac{1-x}{1+x} + 1} + T_s; \tag{8}$$

$$C_g = \frac{P(1-x) - r(1+x)}{2} - xT_s; \tag{9}$$

$$^*C_g \approx \frac{P(1-x) - r}{2}. \tag{10}$$

• 2. *Derivation of minimum nominal period.*

The minimum nominal period, P, was derived in the following way for systems using the basic character-gate method. First, Eq. (6) was transposed into Eq. (11). The value P was solved in terms of character time displace-

*Approximation for relatively small values of r, x, T_s.

ment at nominal speed, speed variation and reset time. The minimum nominal period is given in Eq. (12), and in practice must contain a safety factor to allow for deterioration.

$$T_D\left[\frac{1}{1+x}+\frac{1}{1-x}\right]+2T_s+r=P\frac{1-x}{1+x}\,; \tag{11}$$

$$P=\frac{1+x}{1-x}\left[2T_s+r\right]+\frac{2}{(1-x)^2}\,T_D; \tag{12}$$

$$*P\approx\frac{2(T_D+T_s)+r}{1-2x}\,. \tag{13}$$

Acknowledgment

The author wishes to thank all those who participated in this work and gave helpful advice, including O. L. Lamb, (peak sensing), F. G. Hughes (air lubrication), D. S. Swallow, D. N. Streeter, R. M. Kluess, T. L. Vinson, and R. H. Echelmeier.

Received August 13, 1957