DIGITAL TIME-BASE ERROR COMPENSATOR FOR WIDEBAND TELEMETRY RECORDER/REPRODUCERS[*]

M. S. KLEIN and S. TOMBACK
Advanced Technique Development Group
Communications and Systems, Incorporated
Paramus, N. J.

Summary An advanced development model of a telemetry predetection recording error compensator was designed to reduce flutter and time displacement errors in magnetic tape instrumentation recorder/reproducers so that the final intra-channel time-base error (TBE) does not exceed ±0.1 μsec. The device will operate with recorder/reproducers having bandwidths up to 1.5 MHz and as much as a millisecond of TBE.

The incoming waveform is sampled, digitized, and stored in a memory on a recorded pilot tone at a rate determined by the flutter, using phase-lock techniques. Subsequent readout of the memory, composed of MOS shift registers, at a synchronous rate, produces a replica of the playback waveform with wow, flutter, and TBE significantly reduced.

This technique offers the following advantages over other approaches: direct delay/BW trade-off (i.e. , 1 msec TBE correction at 120 ips, 2 msec TBE correction at 60 ips, etc.), small size, lightweight, low power requirements, and extensive use of MOS and IC devices, amenable to future LSI construction.

Introduction In an ideal transport system, the magnetic tape is moved over the write/read heads at some constant velocity. The extent to which the transport constrains speed irregularities determines the quality of the playback signal. In addition to changing the frequency of a recorded tone, these speed control errors alter the time relationship between pulses and phase modulate complex waveforms. The effect of the speed variations is generally called either wow and flutter, time displacement error (TDE) or, as in this paper, time-base error (TBE), and must be reduced if system performance is to be optimized. Experimental results described in this paper, indicate that performance during playback introduces the major portion of TBE. The TBE compensator must therefore accommodate the characteristics of the reproducer.

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In January 1963, a program was initiated for the Air Force Eastern Test Range (ETR) involving the development and construction of an experimental model of a predetection telemetry tape combiner. Under this contract (AF90 (606)-6739) members of the C&S staff investigated methods for electronically controlling high-speed wow and flutter, Doppler effects, and frequency errors from two or more wideband (1.5 MHz) predetection telemetry tape recordings on playback, and for combining them in precise phase and optimal amplitude to produce one continuous record from a set of overlapping, imperfect recordings. The techniques developed for circumventing these problems represented an advance in the state-of-the-art, particularly in the field of high-speed, electronically-controlled, wide-band delay lines (the delay lines developed, using a binary array of quartz lines, had a delay-bandwidth product in excess of 1,200 and an agility equivalent to 1/2 the speed of light).

This system was designed to combine different data tracks from either the same or two independent machines. Accordingly, the sensing and control was rather sophisticated, relying on simultaneous sensing of the time delay error from timing signals, phase error of a reference tone, and correlation between data tracks, to ensure an absolute time reference.

The above system was inadequate for use as a TBE compensator. Electrically, the S/N attained in the feasibility model was only 30 dB, limited mainly by the switching transients on the analog signal. In addition, the physical limitations of the quartz delay lines used, and the power drain consumed by them, were incompatible with the size and weight constraints of the TBE compensator. It is the purpose of this paper to present some of the insights gleaned from the Telemetry Tape Combiner development, and to set forth the electrical and mechanical considerations and design approach for the TBE compensator.

Technical Discussion

Performance Requirements The TBE compensator is designed to reduce flutter and time displacement errors so that the corrected TBE of a playback signal does not exceed ±0. 1 μsec. The device will operate with recorder/reproducers having bandwidths up to 1.5 MHz and as much as a millisecond of TBE, and 0.5% p-p flutter components from D. C. to 10 kHz.

Electrical Requirements In addition to the above performance requirements, the following electrical requirements were to be met. Input/output connections were to be 75 ohms unbalanced, at a nominal 2 volt p-p level. Harmonic distortion, IM distortion and quantitization noise were each to be at least 40 dB below full test tone level. Phase linearity was to be within 1% , while the amplitude was to remain within ±1 dB over the full bandwidth. Crosstalk due to data modulating the error control signal was to be at least 60 dB down.

Mechanical Requirements The TBE compensator was restricted to a size of 23" H x 19" W x 16" 1) and a weight of 100 lb. The power supplies required for the device were expected to be a significant, if not the major, culprit in meeting these requirements. The intent of the program was to use techniques which would meet these objectives and also be amenable to even further physical reduction at some future date.

Design Considerations

Typical Tape Reproducer Performance As part of the program to develop the telemetry tape combiner system for ETR, C&S personnel ran tests on a group of ten machines located at Cape Kennedy, using an in-house developed test set. The results are shown in the table on the following page.

For the CEC and MINCOM machines, the rate of change of time error appeared to be random, but for all of the AMPEX machines it was quite periodic and usually related to the reel rotation. Slow variations (1 to 2 Hz average) , arising mostly from tension variations at reel rotation rates, represented a large fraction of the total displacement error. At higher frequencies, a nearly white FM spectrum of speed irregularities was observed, up to the corner frequency of the tape reproducer servo system. A narrow line near 10 kHz was often observed in the FM spectrum resulting from tape elasticity and “stiction” (breakaway effect of static friction versus friction in motion) against the heads. The actual time displacement error was extremely small at these higher frequencies, since they are basically FM, rather than timing, disturbances.

Type	Serial No.	Speed (ips)	Average Timing Error	Max. Timing Error (µsec)	Typical Rate (Hz)
CEC 5-752	075	60	300	1000	1
CEC 5-752	080	60	700	2000	0.5
CEC 5-752	003	60	300	800	1
CEC 5-752	013	60	200	300	1
MINCOM CM-107	S18	120	100	150	1
MINCOM CM-107	S18	60	100	350	1
AMPEX FR-600	132	60	100	500	3
AMPEX FR-600	137	60	75	500	2
AMPEX FR-600	133	60	200	300	3
AMPEX FR-600	143	60	225	400	3

An important result was obtained in a special test with the CEC 5-752, Serial Numbers 080 and 013. Serial 080 performed more poorly than the others. Its capstan servo was apparently in need of repair, since it required periodic readjustment by the site technician to maintain lock on playback. A test tape recorded and then played back on this machine resulted in 2000 microseconds error. The same tape played back on Serial 013, the best of the four available CEC machines, resulted in 300 microseconds error. The timing error on playback obviously did not depend on the characteristics of the recording machine. The tape recorded on the poorer machine Serial 080, was subsequently played back on a Sangamo machine which had a high performance capstan servo, with which the maximim timing error observed was ±3.75 microseconds at 60 ips. The playback machine, therefore, apparently determines to at least a first order the timing error. This is an important consideration in tape compensator design: the variable time delay need only accommodate the timing error of the particular playback machines used; timing errors likely to be recorded by down-range machines were of little consequence.

Observations of the frequency of timing error changes have shown that the smaller the timing error, the higher the frequency of change. This is to be expected since low timing error machines have wideband capstan servos.

Time Delay in Phase-Lock Loop The cutoff frequency of low-pass filter in the phase-lock loop must be chosen with care. If it is too high it will permit the control signal to be modulated by the data (nominally, 900 ± 600 kHz) on the track. If it is too low, the filter will introduce excessive time delay to the error signal. If this delay approaches or exceeds 90° at the highest flutter frequency, reductions in loop gain and/or stability will occur.

This is important, as these frequencies contribute significantly to the cumulative flutter. For example, if between 1/5 and 1/2 of the flutter noise energy falls between 5 and 10 kHz, removing only flutter frequencies below 5 kHz will result in an improvement of only 3 to 7 dB in cumulative flutter. The time delay in the feedback loop must, therefore, not approach 25 microseconds (90° at 10 kHz).

Tape Dropouts Most signal dropouts in instrumentation recordings are caused by specks of dust and other contaminants that lift the tape away from the head. The control circuitry must be capable of keeping the error compensator defluttered output within the specified value during moderate periods of signal dropout.

Observed rates of change of delay of ETR machines, rarely exceeded 1 millisecond/second. A control system that stops acting on loss of a reference signal can stay within the allotted ±0.1 microsecond TBE, if the dropout does not exceed 12,000 microinches. Since it would take rather gross contamination to approach this size, this basic approach should suffice. The alternative is design of circuitry that would continue the system clock at the rate it was going at the time of the dropout. This degree of sophistication is not considered necessary to meet the design objective.

Skew Skew, tape stretch between heads, gap scatter, and dynamic skew are factors causing timing errors between different tracks. Because of these errors, it is not adequate to use a control signal on one track to control timing errors on a separate data track.

An error compensator could be made to remove TBE from the control signal, but errors up to more than 1 microsecond are apt to be introduced between tracks, making this approach invalid.

In order to meet ±0.1 microsecond time errors and to act against the expected range of FM components, it is necessary for the overall system to provide a control time on each signal track of the tape. This control time is recorded from the same source as the tape reproducer speed-servo control signal, so that frequency differences will not cause shifting relative to timing.

Frequency Guard Band It is necessary to provide at least a 200 kHz guard band between the nearest data frequency and the control tone in order to accommodate wide sidebands of the control tone while rejecting data components that might modulate the variable delay system. For adequate speed of response, it is also necessary to use a control tone frequency not lower than 100 kHz.

AM Due to Flutter In addition to the undesired frequency modulation of a data signal caused by flutter, there also exists amplitude modulation of the data signal by the same variations in record and playback speeds. These are caused by variations in dF(s)/dt, the time derivative of the flux pattern, as read by the playback head, where s is the distance along the tape. The output voltage, being proportional to dF(s)/dt, is greater for a tape moving faster than a nominal speed, and lesser for a tape moving slower than a nominal speed.

A variable loss device could, if placed in series with the output of the delay line, be used to reduce these AM components, which may be only 46 dB below nominal signal level. The varilosser control voltage could be derived from the delay line control system, since the AM noise and the frequency shift are both proportional to tape motion velocity error. However, it appears that the signal-to-noise ratio of the error compensation will be adequate without this refinement.

System Description With the previously listed design considerations as constraints , the TBE compensator could have taken the form of the original electronically controlled delay lines; i.e., a binary array of fixed delay elements selected by appropriate switching logic. This, indeed, was what was originally planned. The digitization of the playback signal and the use of glass digital delay lines solved the problem of switching transients of an FM signal limiting the S/N. However, a technology reassessment revealed that the art of making MOS shift registers had progressed to the point where they appeared to be the best candidate for use as the delay elements in the compensator, in terms of size, weight, cost, and performance.

A configuration for obtaining electronically variable delay, discarded during the tape combiner contract due to cost considerations, was examined and refined to take advantage of the new MOS capabilities.

A block diagram of the new system is shown in Figure 1. The system operates on the principle of converting analog words to digital form at a rate determined by the flutter on a pilot tone. This variable conversion, accomplished by phase-locking the 6 MHz WRITE VCO to the 100 kHz playback pilot tone, compensates for the instantaneous flutter on the incoming signal. Subsequent D/A conversion at a fixed rate reassembles the data samples with uniform spacing, and the output signal is a replica of the input, but with time variations removed.

This simple system works well for time-base error of less than one-bit time of the READ CLOCK. Larger TBE compensation requires additional storage. The delay line system performs this function. It provides sufficient storage to provide up to a millisecond delay to a 36 megabit data stream (6-bit word x 6 MHz conversion rate).

The chosen sampling speed of 6 MHz is a compromise between the additional bit storage required by high sampling rates and the filtering problems introduced by too low a sampling rate.

The 6-bit digitation of the analog samples causes an average error of 48 dB below full test tone, which meets the quantitization noise objectives.

The following paragraphs describe in more detail the major sub-systems of the TBE Compensator.

Input Buffer The buffer will be an integrated circuit op amp, which provides isolation from the tape machine and permits gain adjustment of the signal to provide optimum performance for the analog-to-digital converter. The circuit is fully compensated to meet the stringent amplitude and phase linearity requirements, and will derive impedances as low as 50 ohms with unconditional stability.

Analog-to-Digital Converter Several vendors make high-speed analog-to-digital converters that could be used in the system. The one chosen uses high-speed successive approximation, with successive delays to overcome tilt. The effective aperture is less than 10 ns, and sample and hold circuits are not needed. Its T^2L, logic is compatible with the logic to be used in the rest of the sample. It is constructed on a single, multi-layer printed circuit board, approximately 5-1/2 in. wide by 10 in. long.

Write Logic A 6 MHz VCO locked to the 1 00 kHz pilot tone via a phase-lock loop supplies clock pulses to the A/D converter. A 6-bit parallel word from the A/D converter is multiplexed into two buffer registers at a 3 MHz rate. This is required, since the MOS shift registers currently do not operate reliably at 6 MHz. The two buffer registers present a 12 bit parallel word to the inputs of the 14 rows of MOS shift registers. A 3 MHz clock signal, developed from the 6 MHz VCO, presents clock pulses to all the rows.

Each shift register section of a row contains 256 bits. In order to fill a row completely, it is necessary to clock each row 256 times. A 14 state counter connected to the 256 counter generates a write enable signal selecting one of the 14 rows determining into which row the data shall be written.

Phase Lock Loop The 6 MHz VCO used in determining the WRITE timing (WRITE CLOCK) is synchronized to a 100 kHz pilot tone recorded on the tape track. This synchronization is accomplished by comparing quadrature components of a divided-down sample of the 6 MHz clock. The error voltage developed by the quadrature phase detectors is filtered and applied to the control input of the VCO.

The use of a quadrature correlation scheme instead of a simpler single-phase feedback loop eases the filter bandpass requirements within the feedback loop with concommitant decrease in loop delay-time.

A phase detector fed with two 100 kHz signals produces a DC error voltage (proportional to the cosine of the phase difference) and an undesired 200 kHz sum signal. If two phase detectors are fed with quadrature components of two 100 kHz signals, respectively, they produce two error voltages whose DC error-components are additive, but whose 200 kHz components are 180° out of phase. Summation of these error voltages prior to applying them to the VCO eliminates the need for a sharp 200 kHz filter in the feedback loop. This effectively reduces the time delay in the control loop by a factor of two, for improved tracking and increased loop stability.

Delay Line and Gating Circuit The delay line and gating circuitry in each row is made up of (12) ÷ 256 bit MOS shift registers, 2 MOS clock drivers and the necessary logic for read-write clock enabling. The MOS shift registers are biased to allow interfacing with TTL components on both inputs and outputs. Because the MOS registers operate on the master-slave principle, it is necessary to provide two clock pulses $\emptyset_1$ and $\emptyset_2$. The two MOS clock drivers convert the system logic levels into polar signals necessary for the MOS clock inputs. Gating supplies control for the read and write cycles. Receipt of a read or write enable allows the respective clock to generate $\emptyset_1$ and $\emptyset_2$, thus shifting information through the registers.

The complete delay line system consists of fourteen such rows.

Read Logic A 6 MHz VCXO supplies stable clock timing to the output D/A converter. A divider from the VCXO supplies 3 MHz clock pulses to the read inputs of the 14 rows of MOS shift registers, and the ÷256 counter. A 14 state counter determines which of the 14 rows will be selected for reading. The outputs of the 14 rows are OR'ed together and sampled at a 3 MHz rate, splitting the 12 bit word into two 6 bit words. These 6 bit words are presented to the input of the D/A converter.

Comparator Circuit It is possible for the average writing rate, derived from the accuracy of the 100 kHz servo loop, to be slightly different from the 100 kHz derived from the READ VCXO. If nothing were done to correct this condition, the difference between the average writing rate and the average reading rate would inevitably cause the delay line buffer to either overflow or underflow, depending on the direction of the frequency offset. This would result in a loss of defluttering capability in one direction and/or a loss of data, depending on the design of the circuitry.

To prevent this from happening, the state of the WRITE counter is subtracted from the state of the READ counter, and the result fed into a 4-bit D/A converter. Appropriate offset is provided so that zero volts out corresponds to mid-range of the delay. Any difference between the two rates of counting will pull the VCXO in the direction of minimizing that difference. Sufficient filtering is provided (a time constant in the order of seconds) to let the VCXO respond to long-term average differences only.

Digital-to-Analog D/A Converter The D/A converter converts the output 6-bit words into a PAM sequence with a 6-MHz sampling frequency, prior to final filtering and buffering.

The D/A converter is of conventional design, except that precautions are taken to maintain good video response. Primarily, this entails the use of high-frequency transistor drivers, with high beta, and design of the resistive ladder network with relatively low-value resistors. It should be noted that response at the 1.5 MHz analog frequency, rather than the 6 MHz sampling rate, is the primary concern. The converter chosen uses resistor values in 2/1 ratios in a current-adding mode and provides satisfactory frequency characteristics and immunity to switching spikes.

Low-Pass (LP) Filter The output spectrum of the D/A converter contains signals from dc to 1.5 MHz and double sidebands of the baseband at all multiples of the sampling frequency (6 MHz). The highest baseband frequency is separated from its closest sideband (6 - 1.5 MHz = 4.5 MHz) by 3.0 MHz. To reduce these unwanted sidebands, a LP filter is provided.

This output filter is a three-section transitional Butterworth-Thompson design, with a 3-dB cut-off frequency of 2.5 MHz. This maintains the amplitude flatness and phase linearity in the passband and affords moderate filtering to the higher order sidebands.

Output Buffer The output buffer is identical to the input buffer, except that there is no gain adjustment for the output circuit.

Packaging The error compensator system is designed for standard 19 inch rack mounting, and requires one 8-3/4 in. high drawer. Power Supplies are mounted separately.

All signal connectors are BNC connectors. Indicator lamps are used to monitor the status of the counters. External control of the error voltage is available to facilitate testing and debugging. All operational controls are on the front panel, all test points accessible, and all plug-in components easily removable.

Conclusions This paper presented the design of a digital compensator for time base error in wideband telemetry recorder/reproducers. Application of the compensator will improve performance of older high-mass machines beyond that obtainable with the newer class of low-mass machines. The performance of low-mass machines, in turn, can be made to exceed that of any existing machines.

The digital TBE compensator is flexible enough to be used where an electronically controlled delay line can enhance system performance.

Additional Investigations The design of the TBE Compensator satisfies the requirements set forth for it. During the development, several other sources of interest for further study presented themselves. Some of these are mentioned below.

Use with Low-Mass Machines Although the existing design would work quite well on low mass machines, the amount of storage required is less than 1/100 of the storage incorporated for the high mass machine to which this design is addressed. Most of the delay available in the present design would not be used. A new design with less TBE capability would be more economical for low-mass machine applications.

More Efficient Coding This investigation did not include examination of improvements attainable by coding techniques. Since a large segment of the cost of the compensator will be in the storage, it is expected that a coding technique such as delta mod or differential PCM would reduce the bit-rate required for reproducing the waveform, and introduce reductions in size, cost, and reliability.

Use as a Predetection Tape Combiner Using the TBE Compensator electronically variable delay line and correlation techniques explored in the design associated with the earlier tape combiner, a new predetection tape combiner feasible for overcoming the limitations of the earlier analog design. This would permit assembly in a significantly smaller package at a fraction of the original cost.

Use in Surveillance Work Although more resolution would probably be needed, either through companding or better encoding, the pay off in improved SIN over conventional machines would be considerable.

Use in Satellite Recorders The availability of a small rugged, reliable and light-weight TBE compensator/deflutterer in the satellite itself would considerably enhance the quality of the channels being received on earth, especially when those tapes are usually speeded up or playback by factors of 20:1.

Delay-Bandwidth Trade-off Although the existing machine works at any playback speed, slowing down the sampling rate to take advantage of the reduced bandwidths at the slower speeds would permit a longer TBE capability inversely proportional to the playback bandwidth. Since the TBE is usually inversely proportional to playback speed, this trade-off could prove quite useful.

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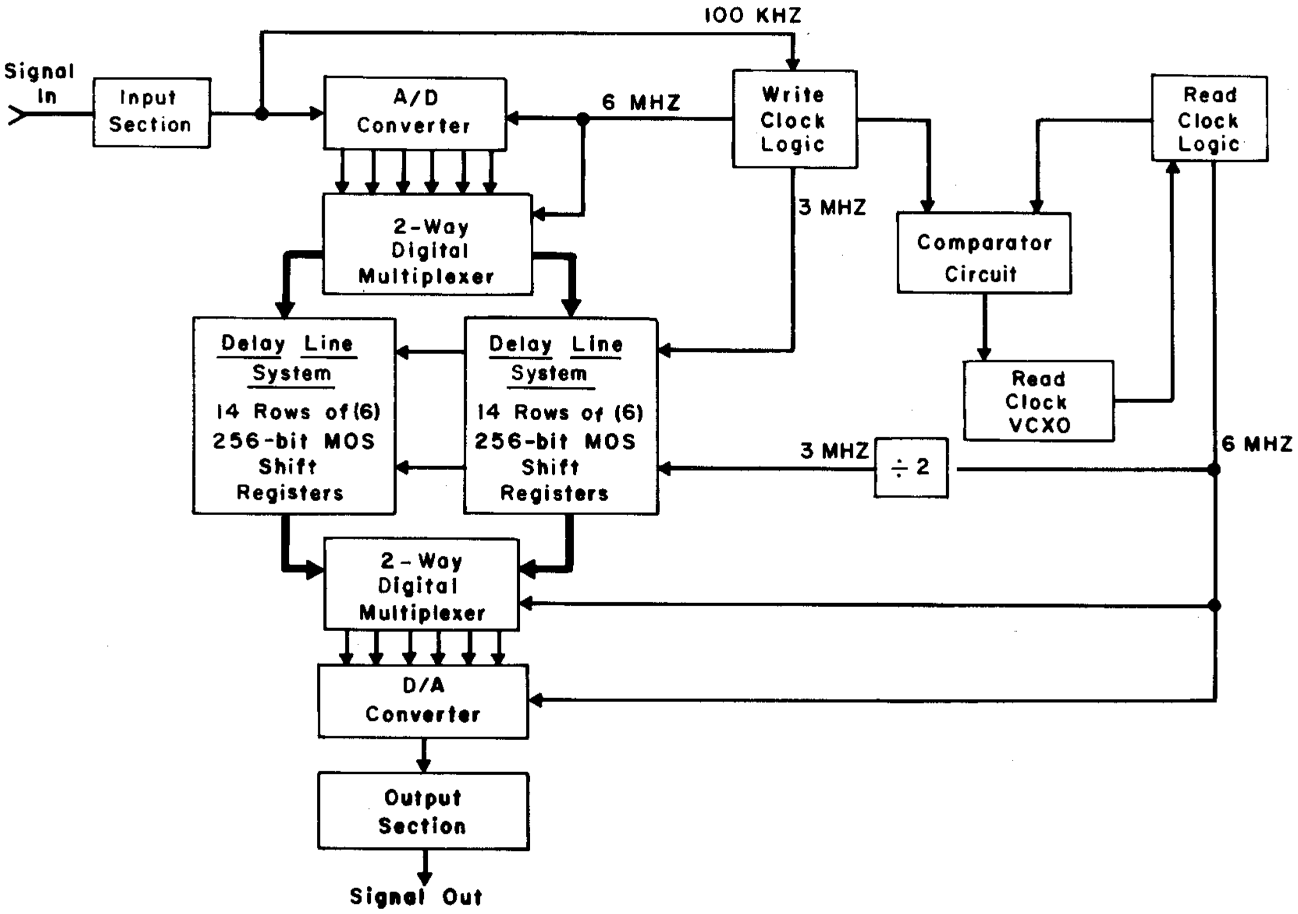

TBE COMPENSATOR
SYSTEM BLOCK DIAGRAM
FIGURE I