HIGH RELIABILITY TAPE RECORDERS FOR SATELLITE, AIRCRAFT & DRONE APPLICATIONS

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Summary A new series of magnetic tape recorders has been developed and flight tested, offering a much higher reliability figure and somewhat improved performance over previous design, especially in terms of long life. Featured is a transport design having only seven moving parts, as compared with three or four times that many in conventional tape recorder mechanisms. Details of this design are described indicating how it is possible to achieve an operating life of 16,000 hours of continuous service in satellite applications. A comparable electronic advance has been in digital record-reproduce techniques where Borg-Warner Controls engineers have developed bit dejittering and servo speed control circuitry that makes possible transmission of recorded PCM or other digital data at high data rates with an essentially jitter-free output from reproducer to telemetry transmitter.

Micro Loop Direct Drive Tape Transports

Introduction A series of airborne tape recorders has been designed at Borg-Warner Controls with the major objective of reducing the total number of moving parts to a minimum, to achieve greater life and improved reliability. In so doing it has been possible to eliminate such previous troublemakers as belts, clutches and, in some cases, gears.

Although in the BWC transport designs, mylar belts are still used for such specialized applications as certain re-entry recorders, and although our company has expended tens of thousands of dollars and thousands of man hours in developing improved techniques for manufacturing good belts, in the new design, belts are usually eliminated. They are used when tape speeds of 1-7/8 ips and lower are required to avoid the cogging problem with the d-c motor.

Similarly, clutches have always been a source of trouble and have been the cause of certain extremely costly failures in flight recorders. Manufacturers of electromagnetic clutches have done a good job for certain applications, but their use in tape recorders, because of end-loading of shafts, proved to be hazardous with any available designs. Some years ago Borg-Warner Controls analyzed all clutches then available and eventually we had to design and manufacture our own clutches to achieve increased life and reliability. But certainly the best solution of the problem was to eliminate clutches, which at best had a life of a few hundred hours and which were components that could result in catastrophic failure of the recorder.

Motors have also been a problem, as well as bearings. By using a design with a direct-drive capstan and low speed pancake d-c motors, it has been possible to predict reliable continuous operation of a recorder for a two-year period, or quite possibly longer.

The new series of BWC tape transports features a single capstan driven directly by one or more pancake d-c motors mounted on the same shaft as the capstan. A multi-tooth gear mounted on this shaft provides a means, with an associated magnetic pickoff, of generating a series of pulses or counts signifying motor speed and serving as the electromagnetically produced signals used, as will be explained later, in our phase lock servo speed control system for controlling tape speed. In one design an optical pickoff is used instead of the magnetic type.

Figure 1 shows the Micro-Loop Tape Drive. Note that the magnetic heads are placed very close to the single drive capstan. This design has been proved to have many advantages, especially in low wow and flutter in both mild and severe environments. With the direct drive, we can operate the d-c motor at relatively low rpm compared with other d-c or a-c tape drives. At a tape speed of 15 ips in a typical transport, the motor rpm figure is only 420 rpm. The motors we use are rated in airborne environments as having a reliable life of about 3×10^9 rpm. Our motor life is many thousands of hours. We treat these motors well electrically. Each motor has four brushes, a redundant set. We apply less than 20% of the maximum rated current,to these brushes; voltages applied are also held at conservative levels.

Tape Drive Magnetic tape is driven by a single wrapped capstan. Tape motion is achieved by wrapping the magnetic tape around a 3/4 inch diameter capstan coated with polyurethane, a high coefficient-of-friction material. This tape drive technique is designated the Micro-Loop drive due to the short span of tape between the read/write head gaps and the driving capstan. This is an important feature especially at low speeds. Scrape flutter can be a serious problem if the tape is not controlled carefully as it passes over the head gap. A diagram of the tape path and transport is shown in Figure 2. Since the tape is controlled by reel servos or negator springs to provide equal tension, only the friction of the tape passing over the magnetic heads must be overcome by the capstan. This reduces wear on the tape and wear on the motor. Stable tape motion through the extremes of temperature is assured.

A premium quality d-c motor is mounted directly to the capstan shaft.

Speed control is achieved by a phase-lock servo. A ratio of 250:1 has been achieved between the lowest record speed and the reproduce speed. This speed change capability has been demonstrated and tested at Borg-Warner Controls and a similar recorder (the Model R-310) is presently being supplied for the OV- I satellite program. Capstan motor velocity is quite stable even at 12 rpm due to the high resolution and gain achieved by the phase-lock servo. The motor speed is controlled within ±0.25 percent of the nominal speed. It should be noted that any jitter present in the digital data may be removed later by the dejittering buffer technique.

The capstan motor is enclosed in an explosion-proof housing as shown in Figure 3. Preloaded bearings are used in the capstan motor, providing resistance to the damaging effects of vibration and shock. The bearings are sealed against contamination by sealed bearings and also by an external seal.

Ball retainers are of the porous phenolic design which provide lubricating oil even after extensive periods of storage.

The capstan drive described is well suited to both analog and digital recorders and provides reliability through the elimination of complex mechanical speed changing mechanisms.

Reel Drive In a typical reel drive, the tape tension provided by the reel motors is 8 ounces ±1.0 ounce throughout the full tape length. This reel tensioning arrangement has the following advantages over most airborne units:

a Gentle tape handling
b Even load on capstan motor
c. More even tensioning (30 - 40 percent variation in negator springs on uncompensated reel drive systems)
d. Protection against moisture
e. Operation in a low oxygen environment
f. Long life

Each reel is driven directly by a d-c motor. The motor is enclosed in an explosion-proof housing as shown in Figure 4. Precision Class 7 preloaded bearings support the reels and also the motor rotor. The design allows each reel drive to be a plug-in module which includes the motor, brake, and reel hub. Tape tension control is maintained by an open-loop servo. Servo tape guides sense the tape diameter to control the voltage to the reel motors.

Braking System Fail-safe brakes are provided to control tape tension in the event of power failure or when power is removed. Self-energizing brakes reduce power consumption of the brake-actuating solenoid. The reel drive and braking mechanism are protected from the effects of moisture and will operate in a low oxygen atmosphere without effect. The reel drive and braking system described provides maximum control of the tape tension with minimum complexity and highest efficiency and will provide long life without the need for maintenance.

Tape Guidance Tape guidance and handling of reels is considered to be of major importance. The tape path is shown in Figure 2. Fixed flange guide rollers control the tape precisely to assure minimum skew. All guide rollers and heads are mounted on a single plane so that tolerances can be controlled precisely. The only sliding friction against the tape oxide occurs at the magnetic heads.

Electronic

Introduction One of the most useful bit jitter specifications applicable to digital tape recorders used in PCM telemetry systems is contained in IRIG 106-66. A limit of cumulative time displacement error (TDE) is established in this document. The TDE of each bit in a specified time interval is measured relative to the average bit start time as dettermined during the preceding interval. This interval is defined as 10 times the time between guaranteed data transitions, or 10 times the maximum expected duration of sequential “ones” or “zeros”.

If a digital tape recorder used in a telemetry system does not meet this bit jitter specification, then it is likely that the ground station receiver will have trouble in locking on the telemetered PCM data, and remaining locked on. This kind of difficulty has been particularly apparent when data rates transmitted are in excess of 50 kilobits per second (kbs).

During the past four years BWC has developed a series of airborne digital recorders including bit dejittering circuitry. A major objective of this work has been to provide PCM machines which would furnish a considerable data storage capacity, usually several million bits, and which would represent a “black box” having essentially jitter-free output on demand. Thus the PCM telemetry system can be built around this black box as if it did not exist except for the specified minimum number of dropouts characteristic of any digital recorder-reproducer.

Because of this dejittering circuitry and its associated phase-lock servo system, it has been possible to place less emphasis on a sensitive precisely tuned tape transport. In fact BWC is making recorders used in such a difficult environment as the re-entry vehicles employed in modern missile test programs where PCM data is recorded and reproduced, and then delivered to the telemetry transmitter in a high-rate digital bit stream -- up to 400 kbs -- that meets the IRIG bit jitter specification.

Operation of a Simple Dejittering System The block diagram, Figure 5, indicates the essential features of a typical bit dejittering system used in several BWC recorders.

A crystal oscillator, either within the recorder or provided from an external source, provides an accurate reference clock which is fed into the block labeled Storage Control Logic. Another clock signal, derived from the tape signal, is played back into the Storage Control Logic.

As indicated on the diagram, these two clocks are processed and used to furnish a servo reference frequency, derived from the crystal clock, and a servo feedback frequency, derived from the tape-recorded clock. These two frequencies are then compared in the phase-lock servo control system used to control the speed of the machine in its reproduce mode.

The solid line marked “Tape Data” on Figure 5 indicates how digital data recorded on a single track is fed into a Storage Network. Several control signals from the Storage Control Logic are applied to the Storage Network in such a way that as the raw non-dejittered data comes in, it starts filling a buffer register under control of an inputting clock (derived from the tape clock) which shifts in one data bit at a time. On the opposite side of the buffer, an outputting clock, derived from the reference clock, shifts out the data which is now dejittered, coming out in a serial bit train having no more bit jitter than the jitter in the crystal clock.

If the bit from the tape which was most recently stored in the register is called the “newest bit”, the “oldest bit” in the register is always shifted out by the outputting clock. Thus the outputting clock shifts the data bits out of the data register in exactly the same order as they have been fed into the Storage Network from the tape. The buffer register included in the Storage Network is of fixed capacity. Data content of this register is variable with time but is never less than 25 percent or more than 75 percent -- to prevent “underflowing” or overflowing.

The outputting clock faithfully retrieves the digital pattern from the tape as long as the buffer register does not overflow or run out of data bits. Since the outputting clock is fixed and crystal controlled, the inputting clock frequency must adjust to assure the proper register content.

The inputting clock has been recorded simultaneously with the data. Therefore the required adjustment of the frequency of the inputting clock is made by properly establishing the tape speed. This speed, as has been described in the section on design of the BWC direct-drive transports, is adjusted by varying the rotational speed of the capstan which is directly driven by a pancake d-c motor.

Now the interrelationship of the dejittering system and the servo system becomes even more apparent, in that the phase-lock servo electronics which establish the motor speed are designed, working in conjunction with the Storage Control Logic, to detect the data content of the buffer register and, by regulating tape speed, to maintain this data content at a nominal 50 percent.

From the standpoint of the flutter spectrum generated on the tape by the transport mechanism, corrections are made to accommodate data rate variations and bit jitter in the following manner:

a. For flutter frequencies outside the bandwidth of the closed loop servo system, the buffer register in the Storage Network has ample capacity to absorb all bit jitter.

b. For lower flutter frequencies, particularly those due to changing loads on the transport resulting in changing tape speeds, the servo electronics can make the appropriate adjustment since this servo will vary motor input from almost zero to full power if necessary.

Several factors contribute to the decision as to how many data bits of storage must be provided in the buffer register. These factors include required data rate; transport flutter worst case, considering the environments in which the transport must operate; maximum TDE due to flutter; ease of implementation; and design margin considered appropriate for the application.

A Larger Dejittering System The dotted lines in Figure 5 indicate how the single-track dejittering system just described may readily be expanded to handle simultaneous dejittering of many tracks of digital input data recorded in parallel. If there are n tracks of input data, then these may be handled by using n Storage Networks as the diagram shows. The mechanization for multiple track dejittering is essentially the same as for a single track.

After all data from the n tracks has been dejittered, the crystal-clocked outputs are usually Ted into a parallel-to-serial converter. This is essentially a shift register out of which the data is fed to the telemetry transmitter.

A parallel to serial converter must be afforded parallel data on demand to produce coherent serial data. The serial clock used by the converter is divided there by n, the number of parallel channels, and supplied to the dejittering system for the reference clock. The dejittering system in turn supplies tape data precisely on demand as required.

As to the design margin provided by BWC engineers in designing the buffer registers for various recorder-reproducers containing bit dejittering, one early model which has been flown successfully on several space vehicles and has returned useful data each time contains a storage capacity corresponding to about 1.1 bits of storage per kbs of output data. This amount of storage capacity even under the most severe environmental conditions encountered by this particular recorder has proved to provide about an 8:1 margin of safety. Hence in a more recent design, there is about 0.5 bit of buffer storage per kbs of output data, which offers a 4:1 design margin under similar environmental conditions. If the environment were much worse, resulting in even more flutter, then greater storage capacity would be required.

It should be pointed out again that in the case of the larger dejittering systems, just as with the single-track system previously described, the data may be clocked out of the final stage -- the parallel-to-serial converter -- by means of an external reference clock just as readily as by means of a crystal clock built into the recorder. This feature can prove useful in certain systems where a master clock is available and required for performing many synchronizing functions in a complex flight system.

An Alternative To Tape Speed Control There are some cases where the best choice is to remove the capstan servo from participation in the dejittering system. For instance, in digital delay applications for re-entry vehicles, where simultaneous record and reproduce takes place, the tape speed control must be independent of the signal from the tape. If the tape signal is used to control speed, the servo system is inherently unstable.

In these instances, it is possible to restructure the dejittering system and make the tape speed control independent of tape signal. Proper data content of the dejittering storage network is now controlled without using the capstan servo to vary the tape speed; tape speed is maintained as constant as possible, but usually indirectly, by controlling motor speed.

The dejittering effect is implemented by modulating the data outputting clock frequency. The modulation of this clock frequency allows the transmission of tape flutter; but the tape flutter and attendant bit jitter can be arbitrarily attenuated.

Figure 6 shows how the crystal-controlled system is modified. The phase lock tape speed servo is replaced by a phase -lock oscillator; this oscillator output replaces the crystal oscillator reference clock. No other change is made to the system.

Output data bits are clocked out of the storage network by the phase-lock oscillator frequency acting through the storage control logic. Input data bits from the tape are clocked into storage by the tape derived inputting clock as before. The Storage Control Logic and storage network are not changed.

Attenuation of the flutter from the tape transport results from the tracking rate limitations of the phase-lock oscillator. The oscillator effects a low-pass characteristic, discriminating against high frequency flutter components.

When viewed as a servo mechanism, the phase-lock oscillator has a second-order low pass closed-loop response characteristic with critical damping and a final rolloff of 40 db per decade. The amount of transport flutter transmitted is governed by the spectrum of the flutter, and the bandwidth of the phase-lock oscillator.

The bandwidth of the phase-lock oscillator can be set arbitrarily low. As a result, the transmitted flutter can be reduced as required to meet applicable bit jitter specifications. The bandwidth setting can be determined by calculations based on the applicable bit jitter specifications, the bit rate, the flutter spectrum produced by the tape transport in the applicable environment, and the desired bit jitter design margin.

Once the bandwidth has been set, the amount of time displacement error (TDE) to be accommodated by the storage network can be determined, and the amount of required data storage ascertained.

Some Applications Of Bit Dejittering Both the crystal oscillator controlled and the phase-lock dejittering systems have been implemented in flight hardware by BWC. Some examples follow.

The Model R-150 was the first application of crystal oscillator control. Five channels of data from each of five tape tracks are simultaneously dejittered. Data is outputted after serialization at slightly less than 150 kb/sec. Bit jitter is immeasurable by conventional techniques.

More recently the model R-310 was fitted with crystal oscillator controlled bit dejittering. The techniques of implementing the system were updated to take advantage of the advances in integrated circuit technology. Jitter-free data Ls reproduced at about 70 kb/sec.

Phase-lock dejittering systems have been utilized in two high environment re-entry loop-delay recorder/reproducers, Models R-314 and R-318. The Model R-314 has a phase-lock bandwidth of 5 Hz, and sharply attenuates transport flutter since virtually all flutter components are well above the 5 Hz limit. The result is data at about 250 kb/sec which exhibits less than ±400 nanosecond jitter at the 150th bit. The Model R-318 has a wider phase-lock bandwidth, having been tailored to a less stringent specification, and although substantial flutter is transmitted, it performs well within the design specification.

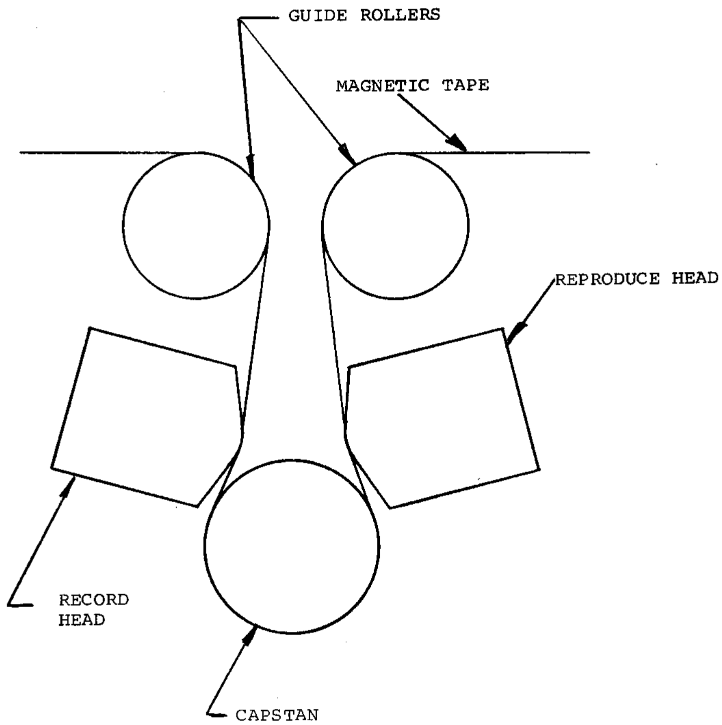
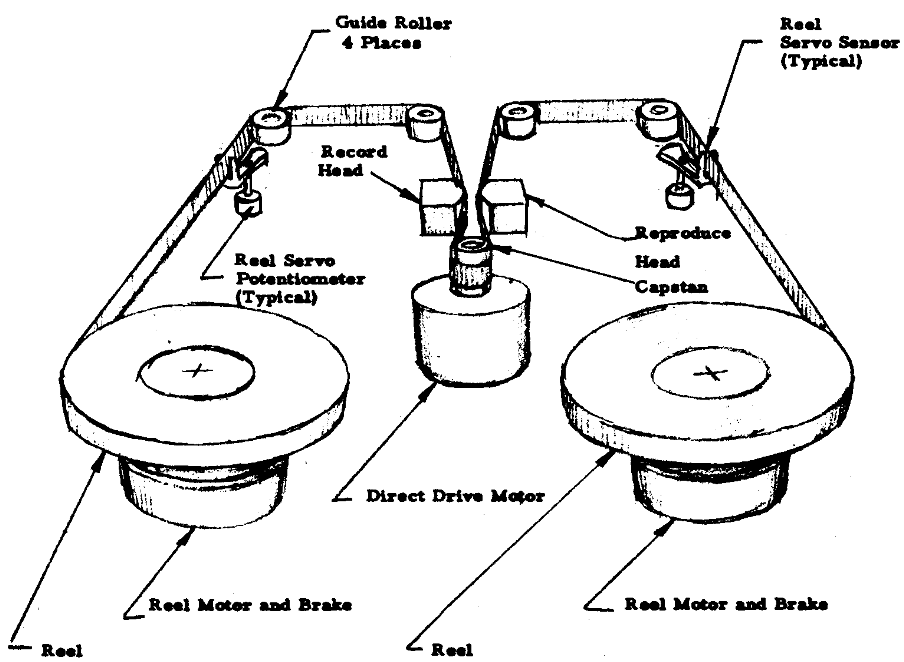


Figure 1 MICRO-LOOP TAPE DRIVE



Tape Path and Transport Diagram
Figure 2

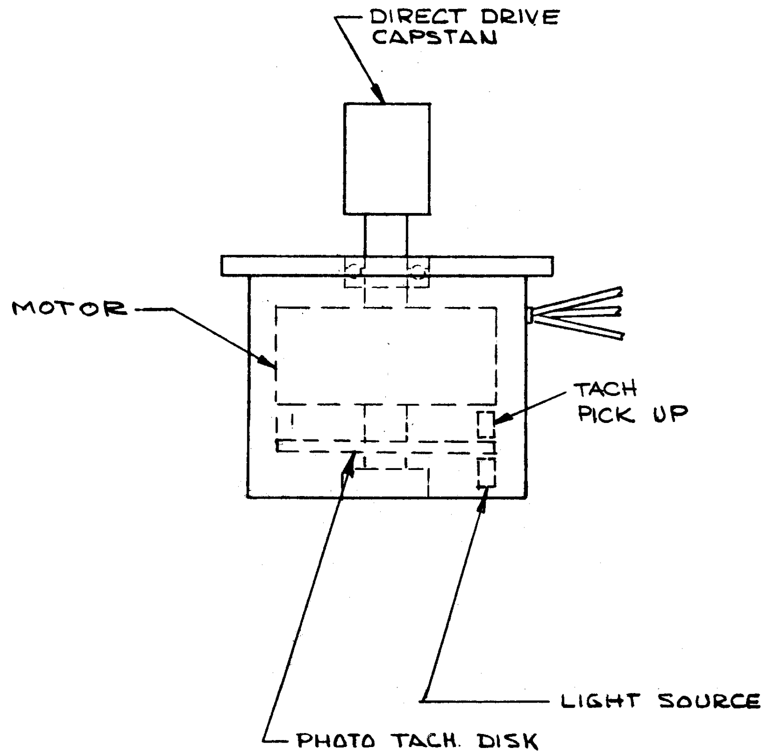


Figure 3 Capstan Motor Housing

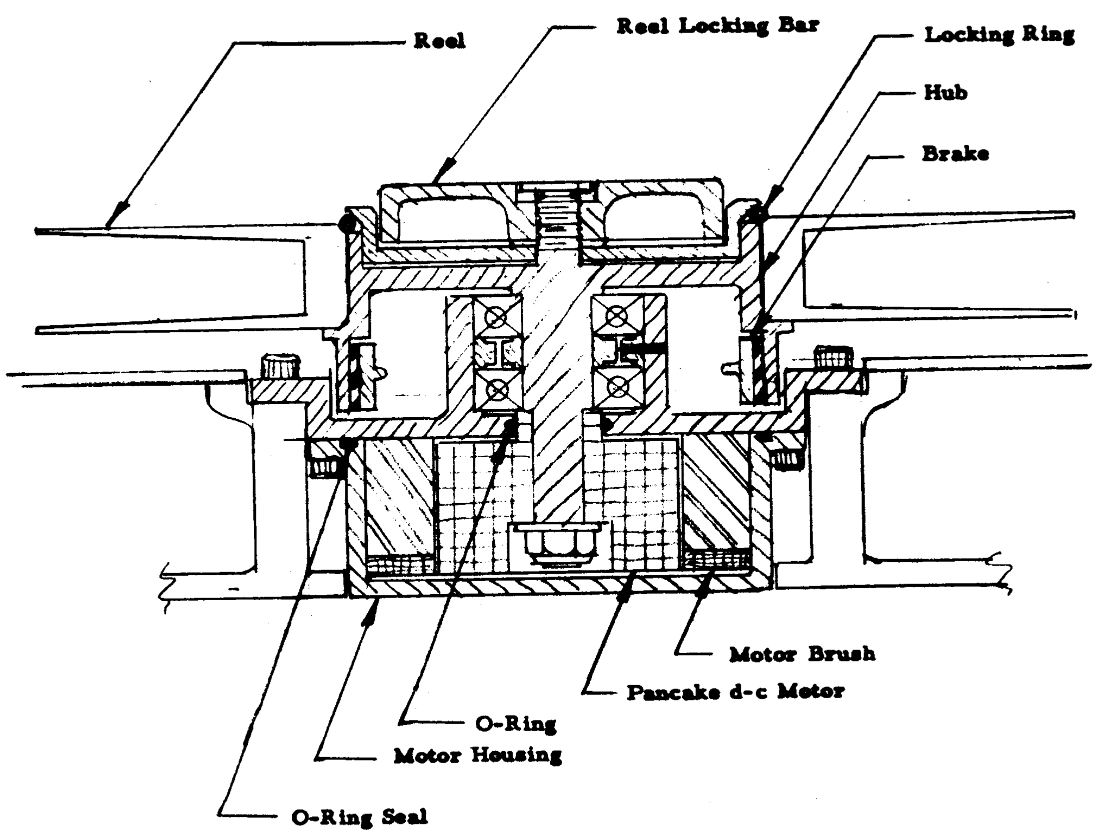


Figure 4 Reel Motor Brake and Hub Assembly

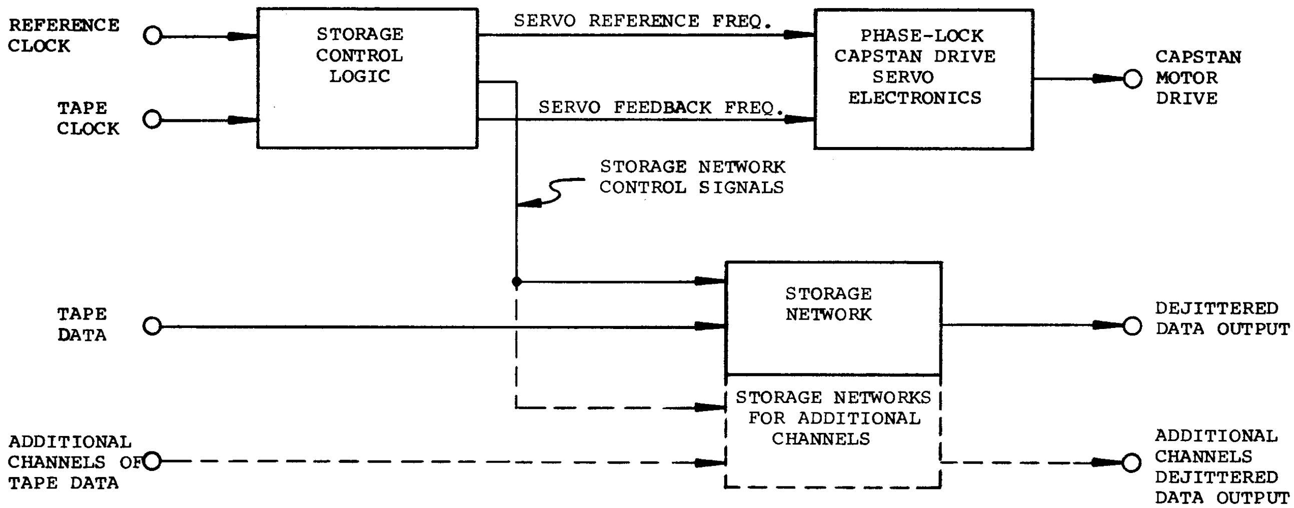


FIGURE 5 SINGLE OR MULTI-CHANNEL BIT DEJITTERING SYSTEM

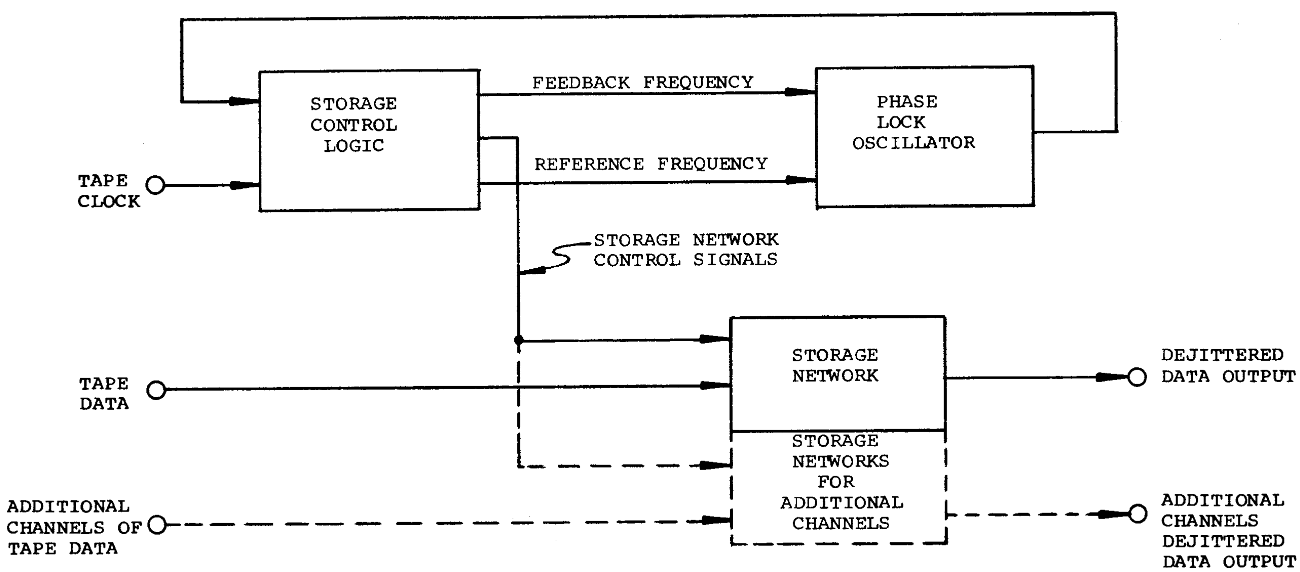


FIGURE 6 SINGLE OR MULTI-CHANNEL PHASE-LOCK BIT DEJITTERING SYSTEM