Mechanical design of the cartridge and transport for the IBM 3480 Magnetic Tape Subsystem

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The IBM 3480 Magnetic Tape Subsystem has achieved significant improvements over its predecessor, the 3420, in speed, data density, and floor-space requirements. The 3-megabyte-per-second data rate of the 3480, which is 2.4 times that of the 3420, was accomplished through the use of chromium-dioxide tape stored in a compact, single-reel cartridge threaded to a take-up reel. A sixfold increase in data density over the 3420 allowed reduction of the size of the 3480 reel, which was essential for rapid acceleration of the tape in the 3480's reel-to-reel transport. The increased data density also demanded substantial improvements in tape guiding and tape-motion control. This paper describes how mechanical analysis and design contributed to the achievement of these advances and aided in overcoming the ensuing problems.

Introduction

Since the introduction of the IBM 3420 Magnetic Tape Subsystem [1], the demand for storage has increased considerably. Concurrently, signal-processing and error-control techniques have also made significant advances. Such advances have made it practical to consider means to increase the density and data rate in magnetic recording systems. In the 3420, data are recorded at a density of 6250 bytes per inch using a nine-track format in half-inch-wide magnetic tape which is wound on a 10½-inch-diameter reel, resulting in a reel capacity of 165 megabytes. Tape tension is controlled by vacuum columns. The present work was part of an effort which included increasing the number of tracks on the tape and decreasing the diameter of the tape reel in order to achieve an increase in the density and data rate.

The moment of inertia of a constant-density disk varies as the fourth power of its radius; the electrical power needed to achieve a specific linear acceleration at the outer edge of such a disk, say to $100\ m/s^2$, varies to the sixth power of its radius. Thus, the radius of a tape reel markedly affects the electrical-power requirements of a tape drive. This is avoided in the 3420 by rapidly accelerating the tape in the vacuum columns. The massive reels of the 3420 need only accelerate slowly, time being allowed for this by the mechanical buffering which is achieved through use of its vacuum columns.

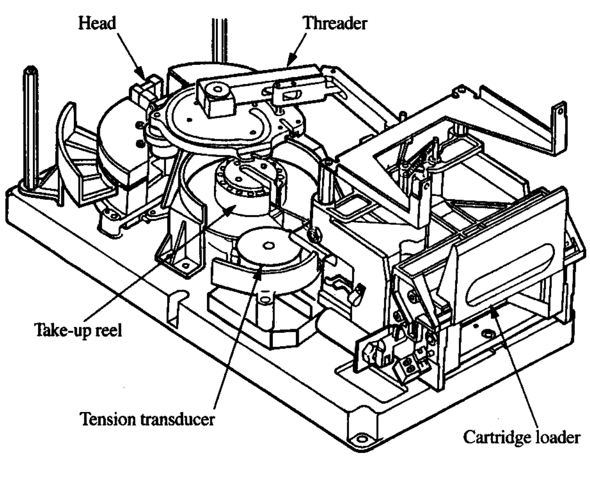

Figure 1

Internal view of the 3480 tape drive.

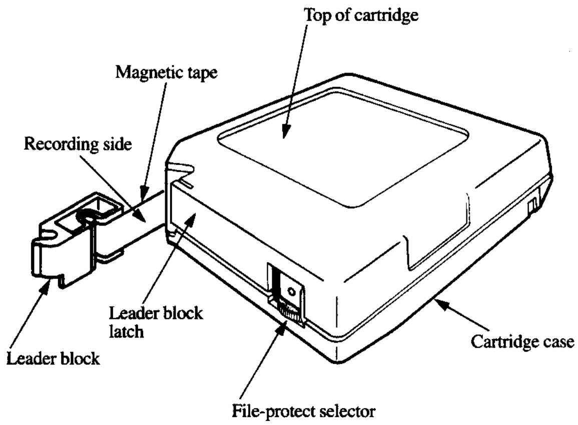

Figure 2

Single-reel cartridge and leader block.

To avoid use of the relatively costly and sizable vacuum columns without incurring an appreciable electrical power increase, the reel diameter needed to be reduced. Such a reduction would permit a trade-off allowing use of an increased acceleration but requiring a higher data density in order to avoid reduction in data capacity. In the approach which was taken, a compromise among reel size, tape guiding, and tape motion was reached by using a 100-mm-diameter reel and a signal density of 972 flux changes per millimeter. Possible use of a two-reel cassette was ruled out in favor of using a single-reel cartridge. Thus, high-volume cartridge cost was traded off against the addition of a tape threader in the drive. The use of half-inch-wide chromium-dioxide tape [2], an 18-track format and a 3800-byte-per-inch density made it possible to achieve a 200-megabyte capacity at a 24K-byte block size.

Figure 1 shows an internal view of the tape drive which was developed. Threading is accomplished by a pantocam threader that guides the leader block of the cartridge, to which the tape is attached, around the tape path. The leader block is inserted into the take-up reel, and the tape is brought to the correct tension to complete the threading operation. Guiding of the tape over the magnetic head is accomplished by compliant guides seating the tape against reference flanges.

The remainder of this paper pertains mainly to these mechanical components and associated considerations in their design.

Cartridge

The single-reel tape cartridge which was developed [3] is depicted in **Figure 2.** It contains internal structural ribbing to provide the needed strength with minimum weight, thus reducing shipping and handling costs. Its design was adapted for automated molding and assembly processes to further reduce costs. Its small size permits a significant increase in the number of tapes that can be stored in a typical tape library.

- *Leader block*

The outer end of the magnetic tape is fastened to a plastic leader block [4] which serves the following functions:

- The leader block snaps into place to close the cartridge opening [5] when the cartridge is not in use (Figure 2), protecting the magnetic tape against contamination by debris.
- A threader pin **[Figure 3(a)]** is used to thread the tape through the path. As the cartridge is being loaded into the 3480 drive, this pin engages the leader block **[Figure 3(b)]**. The threader pin then pulls the leader block and attached tape through the tape path to thread the drive. This threading operation is completed when the leader block is automatically inserted into a slot in the drive take-up reel **[Figure 4(a)]**.
- When the leader block is threaded into the take-up reel, its outer surface becomes a portion of the hub of the take-up reel [Figure 4(a)]. The leader block has designed-in compressibility [3] to help reduce tape deformation at the interface of the take-up reel hub and the leader-block **[Figure 4(b)]**. Undesirable tape deformation must be avoided because it results in a loss of signal caused by tenting of the tape over the magnetic head **[Figure 4(c)]**.

Because the cartridge leader block was intended to facilitate automatic threading of the tape drive and to form an integral

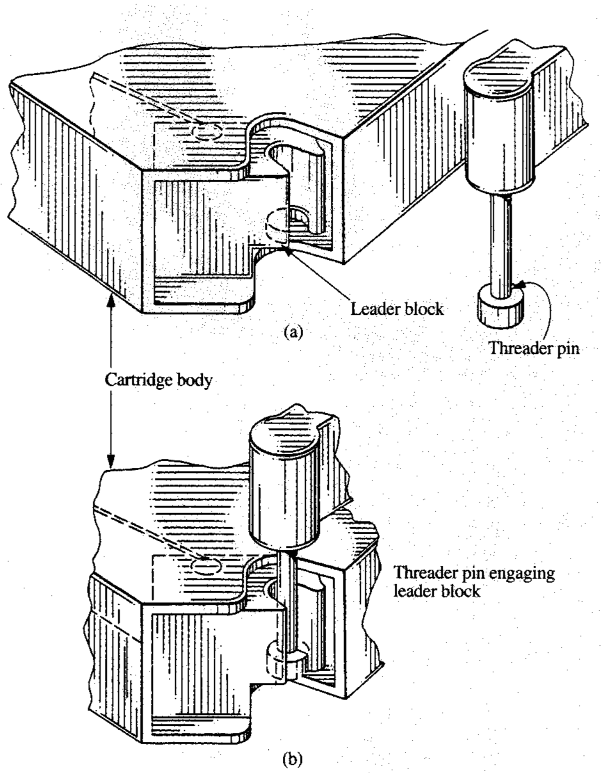

Figure 3

Cartridge leader block and threader pin.

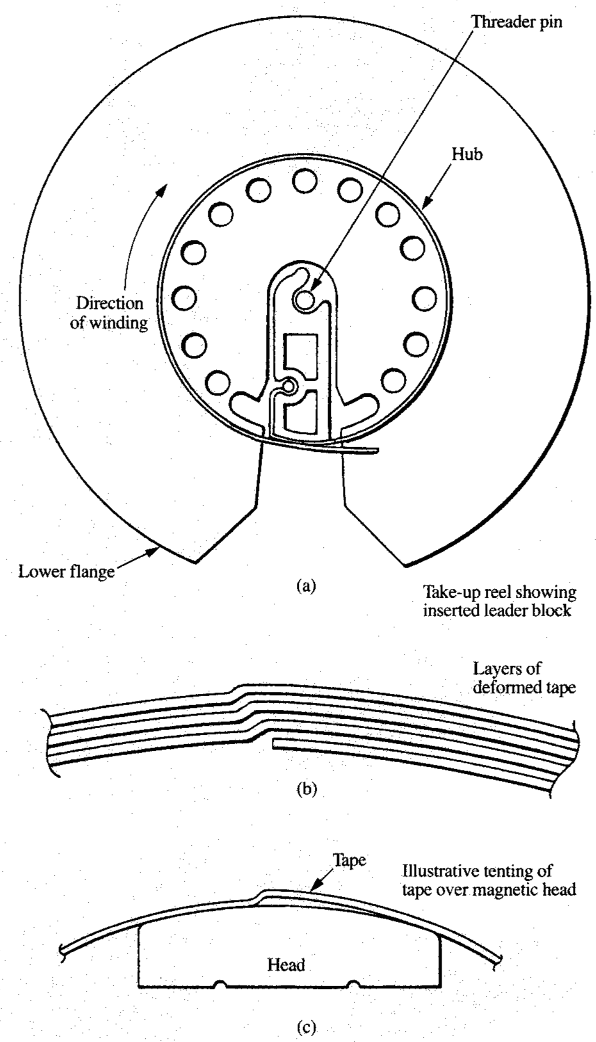

Figure 4

Leader block and take-up reel—depicting use of leader block to reduce tape deformation.

part of the take-up reel, it was carefully designed to meet cartridge, threading, and take-up reel constraints.

• *File-protect mechanism*

The file-protect mechanism is a thumbwheel selector on the edge of the cartridge (Figure 2); it can be set to either of two positions. When the selector is in the file-protected position, the cartridge can be used only for reading data. When the selector is in the unprotected position, the cartridge is unprotected and can be used for both reading and writing. Human factors heavily influenced the design of the switch. Because it is manually rotatable and cannot be removed from the cartridge, no special tools are required and there are no loose parts to be misplaced. Finally, the thumbwheel is recessed into the body of the cartridge, so that it is protected from accidental damage and movement.

• *Cartridge loading*

The cartridge is seated on a magnetic clutch [6] by means of an articulated tray. The clutch sharply reduces stray magnetic flux by means of a pole piece that penetrates into the center of the reel, along its axis of rotation. As the cartridge is seated on the clutch, the internal brake mechanism of the cartridge [**Figure 5(a)**] is disengaged by the magnetic pole of the clutch to allow free rotation of the reel [**see Figure 5(b)**]. Simultaneously, the leader block (now part of the cartridge) is slipped over a threading pin which is part of the pantocam threader (see Figures 3 and 6).

The internal brake mechanism of the cartridge, a spring-loaded brake button [Figure 5(a)], prevents reel rotation when the cartridge is not in the drive. The brake button is released automatically by the magnetic clutch of the drive as the cartridge is loaded into the drive [Figure 5(b)] and is automatically re-engaged upon removal of the cartridge from the drive [Figure 5(a)]. The tip of the brake button must act

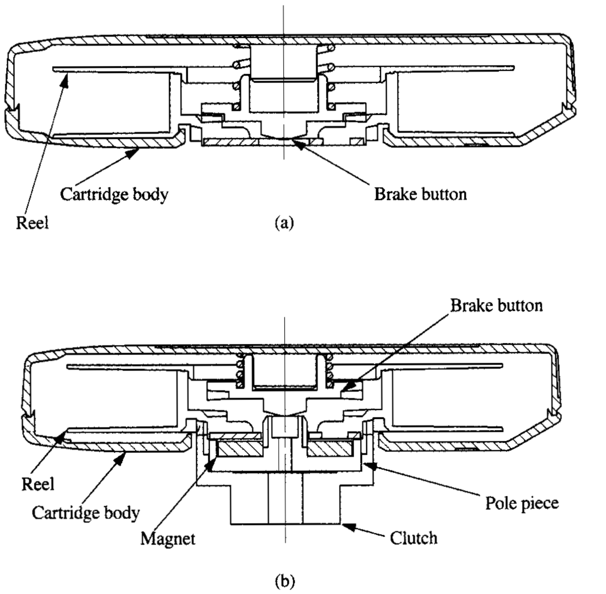

Figure 5

Reel clutch and brake button: Part (a) depicts unloaded cartridge; (b) depicts cartridge loaded in the tape drive.

as a bearing surface against the drive clutch during reel rotation, when the cartridge is loaded into the drive. To achieve this, the brake button is molded from a wear-resistant, low-friction polymer.

- *Interlayer slip*

Exposure of the cartridge to environmental stress can cause a loss of tension in the tape [7]. This could degrade interlayer friction enough to cause shifting or slipping of tape layers when the hub of the reel was accelerated or decelerated.

The reel-to-reel configuration of the 3480 has no mechanical buffering. With regard to its position and velocity controls, it is assumed that there are no loose layers of tape that will slip during the operation of the tape drive [8]. Furthermore, an interlayer slip could cause permanent damage to the tape, and creases commonly known as z-folds might form as a result [9, 10]. These creases could tent over the magnetic head, as illustrated in Figure 4(c), causing a loss of magnetic signal.

Accordingly, a suitable hub material had to be selected. Reels with hubs of various materials were evaluated, leading to the selection of a composite, glass-filled polycarbonate, which gave the smallest probability of interlayer slip in the operating environment of the 3480 [11]. This material is a commercially available polymer which best matches the thermal and hygroscopic behavior of the tape over the range of environments to which it is exposed.

Upon loading and threading, the drive winds five wraps of tape onto the take-up reel and then executes five special start-stop-backhitch operations [12]. Each start is a stress test involving the use of high acceleration—necessary because of possible prior exposure of the cartridge to severe environmental stress. If an interlayer slip occurs during this high-acceleration test, it is detected by the pulses from the drive motor's fine-line tachometer. A flag is set to indicate whether or not the reel has slipped. If the tape shows interlayer slip, a Locate EOT (end of tape) command is executed, followed by a high-speed rewind to subject the tape to appropriate tension before use [10].

Cleaning cartridge

The cartridge for the 3480 substantially reduces the time required to clean the drive and minimizes operator involvement. Drive cleaning is enhanced through the use of a modified tape cartridge that contains a half-inch-wide fabric.

A cleaning cartridge is distinguished from a magnetic-tape cartridge by the use of drive sensors. When the cleaning cartridge is loaded into a 3480 drive, a notch in its body prevents the "cartridge present" state of the drive sensor from detecting the presence of a cartridge. However, the file-protects switch of the drive will indicate that the cartridge is file-protected. The microcode interprets the loading of this nonexistent, yet file-protected, cartridge as meaning that the cleaning cartridge has been inserted.

After the cartridge has been loaded into the 3480 drive, its fabric runs back and forth along the same path the tape travels, minimizing the propensity for buildup of contamination. The average life of the cleaning cartridge is estimated at 500 cartridge loads. Many of the functional benefits of the cleaning cartridge are related to operator ease and productivity. Under normal conditions, an operator takes five minutes to clean a 3420 drive. With the 3480 cleaning cartridge, the time is reduced to approximately 40 seconds. The cleaning cartridge eliminates the need for operators to use various cleaning materials currently required for manual cleaning.

In summary, the cleaning cartridge can control the possible excessive buildup of contamination in the tape path. The migration of foreign or magnetic-tape particles could contaminate the tape path or data cartridge, resulting in poor drive performance. Under the automatic control of the drive, the cleaning process takes less time, requires less operator involvement, and decreases the potential for human error.

Pantocam threader

The tape is threaded through the drive by a pantocam linkage (**Figure 6**). This device uses a cam to control the articulation of a hinged beam [13]. The hinged region is locally strengthened by a four-bar linkage.

Initially, the threader pin [14], located at the extremity of the linkage, accepts the leader block as the cartridge is being loaded onto the drive clutch. The pantocam threader then pulls the leader block, to which the tape is attached, around the tape path and inserts the leader block into the take-up reel. The take-up reel is aligned for insertion of the leader block by a light-emitting-diode–phototransistor (LED–PTX) pair. This alignment is important to prevent the leader block from crashing into the hub of the take-up reel. After the tape is threaded, the threader pin remains engaged with the leader block, resting in the axis of rotation of the take-up reel. Thus, in the unloading operation, the pantocam linkage does not again need to locate the leader block.

Unloading of the tape consists of repositioning the take-up reel to the alignment dictated by the LED–PTX pair, retracing the leader block through the tape path, and reinserting the leader block in the cartridge. The supply-reel motor is biased to spool in the tape during this operation.

Take-up reel

The take-up reel accepts the leader block, the outer edge of which forms a portion of its outer hub [Figure 4(a)]. This interface is especially significant, for serious plastic deformation of the adjacent tape could result if a discontinuity were to exist between the take-up reel and the leader block.

On either the supply or the take-up reel, winding of the tape under tension leads to a condition in which each new layer imposes a radial compressive stress on previously wound layers [7]. These radial stresses, exerted on the inner layers, can be a problem whenever a discontinuity is formed in the cylindrical surface of the hub [Figure 4(a)] or at the point at which the end of the tape is attached to the reel hub of the cartridge.

This problem results in a plastic deformation of the tape [Figure 4(b)] in the region of the discontinuity; the latter can cause the tape to tent [Figure 4(c)] over the magnetic head, resulting in a loss of magnetic signal. The degree of tenting and the seriousness of the plastic deformation are related directly to the size of the discontinuity, the radial stresses resulting from wrapping the tape under tension, the length of time the layers are exposed to the discontinuity, and the material from which the hub is manufactured.

Decoupler

Staggered wraps occur mainly during high-speed rewind at 4 m/s. The tape stacks against one flange of the supply reel and then against the other because of air entrapment, tape curvatures, and unbiased tape guiding. When the tape is spooled from the reel and fed forward to the head, such in-plane lateral movement causes off-tracking, skew, and minor shocks in the tape. The decoupler is designed to isolate the shock and absorb the lateral motion. The decoupler also absorbs the change in radius of the supply reel, from a full reel to an empty one. At the exit of the decoupler, variations in the tape guiding caused by the cartridge (such as the way it is seated on the magnetic clutch and the degree of staggered wraps) are kept to a minimum [15].

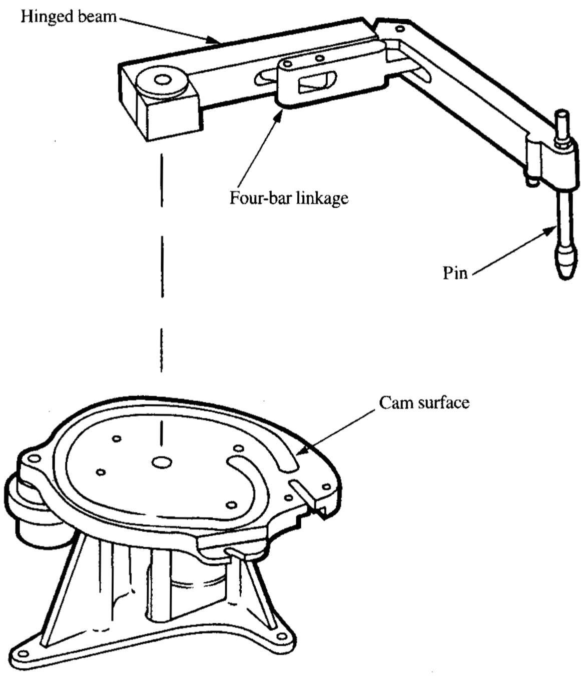

Figure 6

Pantocam linkage for tape threading.

Figure 7 shows the various elements of the decoupler. The decoupler is designed to support the tape by means of two hydrostatic air-bearings at the inlet and the exit. At the midpoint, the tape is pulled in with a vacuum pocket to form an omega-shaped loop. This miniature vacuum column softens the tape path and absorbs transients in tape stretch and tape slack. The lateral movements from staggered wraps turn into differential stretch and slack between the two edges of the tape. During high-tension transients, the tape is observed to move slightly in and out of the vacuum pocket.

A unique feature of the miniature vacuum column is its capability of holding a constant tape length within the response time of the drive's dynamics. The servo system controls the tape position by means of an optical encoder mounted on the motor shaft of the cartridge reel [8]. If the length of tape between the cartridge and the head can vary, the position control at the encoder will not be able to control the tape's location at the read/write head. Maintenance of constant length is accomplished by means of a triangular hole in the lower flange. The edge of this hole defines a step,

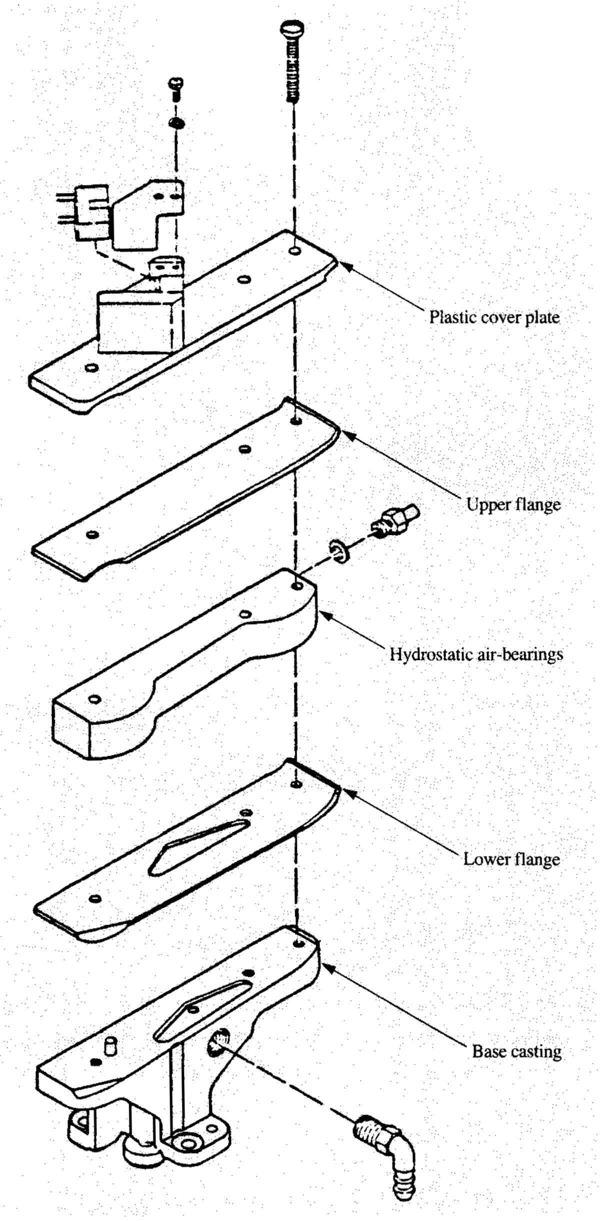

Figure 7

Decoupler elements.

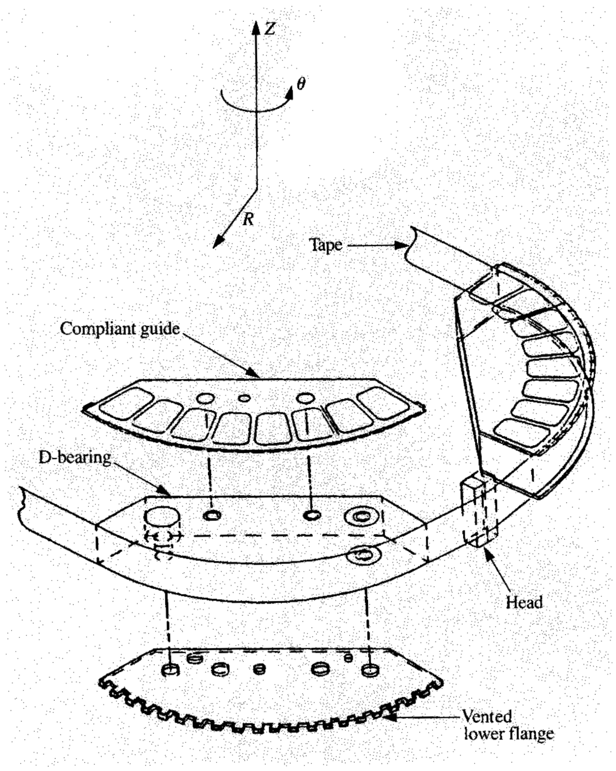

Figure 8

Tape-guiding mechanism.

where the suction force on the tape jumps between two distinct levels. If the tape enters the vacuum pocket beyond the triangular hole, a large amount of venting causes the suction force to drop to a minimum to reduce this overpenetration.

Head-guide mount

A tape drive must be provided with guides, one on each side of the magnetic head, to move the magnetic tape repeatedly across the read and write elements of the head. The tape-guiding mechanism is illustrated in **Figure 8**. Each of the guides is compliant and exerts a distributed load on one edge of the tape. This causes seating of the opposite edge of the tape against a reference lower flange. The tape is also wrapped around a cylindrical guide surface, or D-bearing, to increase its buckling strength (resisting the compressive load of the leaf spring). A hydrostatic air-bearing causes it to float on a thin film of air to minimize friction [16].

• *Compliant guides*

Each compliant guide consists of a leaf spring which has been photoetched from thin, nonmagnetic stainless steel. The elasticity of the leaf spring is controlled by the number, thickness, and length of the radial fingers.

The compliant guide seats the tape against the reference lower flange by exerting a distributed load on the edge of the tape. This load, q, opposes the vertical motion of the tape, Z, proportional to the spring rate, K, of the compliant guide along the angle of wrap of the D-bearing, θ, and is given by

$$q(\phi) = -KZ(\phi) \qquad 0 < \phi < \theta. \tag{1}$$

From this equation, we see that the compliant guide exerts a restoring force on the edge of the tape. As the tape lifts the compliant guide, the guide pushes back the tape.

In addition, each compliant guide is preloaded by a bend in each finger. This introduces an initial preload, q^*, on the edge of the tape. The initial preload is then superimposed on the loading caused by the vertical motion of the tape, which is given by

$$q(\phi) = -KZ(\phi) - q^* \quad 0 < \phi < \theta. \tag{2}$$

A model of the tape-guide interaction was derived, showing the compliant guide force that results from the lateral motion of the tape. The compliant guide deforms in a spiral fashion in the z-direction when the tape is perturbed at a reel (due to a staggered wrap or a tolerance mismatch). Using a noncontact capacitance probe, actual compliant-guide deformation was measured for a 10-mN lateral force, as shown in **Figure 9**. As indicated in the figure, theory compared well with experiment, allowing application of the model to the design efforts.

Because of the compliant-guide deformation, the analysis of the tape-guide interaction was much more complex than the simple beam equations needed to study pin guiding [16]. Shear-moment and differential-equilibrium relationships were used to derive an ordinary nonlinear fourth-order differential equation:

$$(EI/KR^4)[d^4(q)/d\phi^4] + q = 0.0 \tag{3}$$

The equation has a closed-form analytical solution (shown below), which contains trigonometric and exponential terms. It expresses the distributed load, $q(\phi)$, exerted on the tape by the compliant guide as a function of guide radius, R; guide spring rate, K; guide wrap angle, θ; tape areal inertia, I; and Young's modulus, E, of the tape:

$$\begin{aligned} q(\phi) = {} & A \exp(Ra\phi)\cos(Ra\phi) \\ & + B \exp(Ra\phi)\sin(Ra\phi) \\ & + C \exp(-Ra\phi)\cos(Ra\phi) \\ & + D \exp(-Ra\phi)\sin(Ra\phi), \end{aligned} \tag{4}$$

where $a = \sqrt[4]{K/4EI}$, $0 < \phi < \theta$.

Two of the boundary conditions of the above solution relate to the moment and force exerted on the tape at a reel, e.g., that caused by staggered wraps or motor-shaft misalignment. The last two boundary conditions imply no lateral or skew motion of the tape at the magnetic head. Solution of Equation (4), under the above boundary conditions, made it possible to select a spring rate K for the compliant guide which was compatible with the geometry of the drive and the physical characteristics of the tape.

• *D-bearings*

Each D-bearing is a 90° segment of a cylinder, having a height which is slightly less than the width of the tape. Therefore, an edge of the tape protrudes above the top of each D-bearing; this protruding edge is in contact with the compliant guide overhead. The compliant guide cannot exert too much force on this unsupported, protruding edge; otherwise, tape buckling would occur.

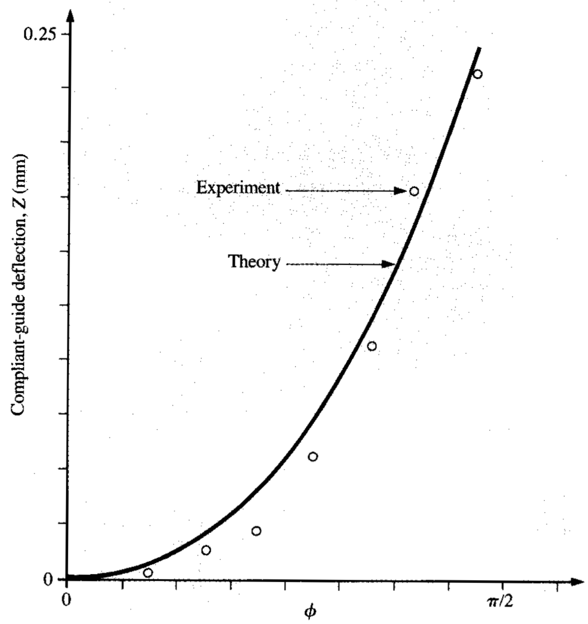

Figure 9

Compliant guide deflection: theory and experiment.

Wrapping the tape around a cylindrical surface strengthens the unsupported tape edge against buckling, and more tape-edge load can be tolerated than if the compliant guide exerted its distributed load on a straight section of the tape. However, the wrapping of the tape presents a problem. The following belt equation [18] shows that the friction drag exerted on a tape wrapped around a cylindrical surface is an exponential function of the Coulomb coefficient of friction, μ, and the wrap angle, θ:

$$\textit{Frictional drag} = (e^{\mu\theta} - 1). \tag{5}$$

This exponential dependence results in the following: If the angle of wrap is large, i.e., 90°, the coefficient of friction must be exceedingly small to prevent excessive drag from degrading the performance of the tape-motion servo system.

Experimentation indicated that a hydrodynamic air bearing [19] (a thin film of boundary-layer air) never formed under high wrap-angle conditions. Furthermore, the Coulomb coefficient of friction could not be reduced below 0.1 through the use of metallurgical surface treatments. The only means found to be suitable for achieving the required reduction in the coefficient of friction was to float the tape on a pressure-fed thin film of air by means of a hydrostatic air-bearing.

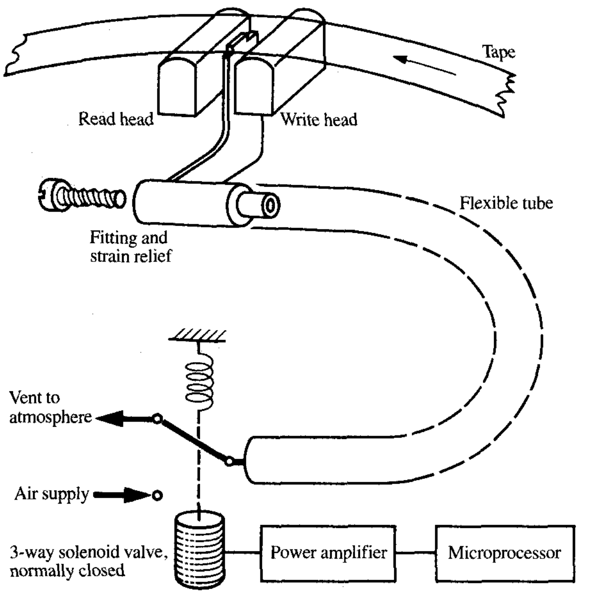

Figure 10

Tape lifter.

The tape is suspended on a thin film of air forced between the tape and the surface of the D-bearing. This air is injected under pressure through a matrix of small ports in the cylindrical surface of the D-bearing. This provides low friction, enabling the compliant guides to seat the tape against the reference lower flanges.

• *Lower flanges*

The lower flanges are used on the head-guide mount, one on each side of the head. These reference, or datum, surfaces are composed of thick, nonmagnetic material. (Unlike the thin compliant guides, the lower flanges are permitted no flexure.) The lower flanges are vented with radial grooves to provide an improved hydrostatic air-bearing.

To ensure sufficient control, the tape is seated on each lower flange for several tape widths of arc. This aspect ratio of arc-guided length to tape width ensures stabilization of the tape and dissipation of moments in the tape in order to pass the tape reliably over the magnetic head. Thus, skewing (angulation) of the tape and lateral (off-tracking) motion of the tape are held below a level that would cause a data-reliability problem.

• *Lateral and skew settings*

The magnetic head must be aligned with the reference lower flanges or the tape will be wrongly steered by the same guides intended to stabilize it. The head is placed laterally, by a shimming process, and then made to penetrate the plane of the tape to provide the correct wrap angle for hydrodynamic lubrication [19].

Because of the 3480's high linear density and read track width, the skew of the head relative to the reference lower flanges is the most critical of the necessary alignments [20]. In the past, skew tapes were used to align the head with the drive. However, the generation of precision skew tapes required that the signal be read both from the front side and through the back side of the tape for purposes of self-checking. However, because the high-density signal on the chromium-dioxide tape could not be read through the back side of the tape, an optical alignment method was chosen. The lower flanges of the head-guide mount are aligned with an axis of a precision x-y stage of a high-powered microscope. The microscope is used to observe the outer write tracks in reference to the other axis of the x-y stage. Because the x-y stage axes are perpendicular, the write tracks of the head can be properly angled perpendicular to the lower flanges. (This small-angle rotation, accomplished by a skew plate and a differential screw, was only one possible method [21] for aligning the head.) A functional test tape (unverifiable skew tape) is then used as a validity check of the optical alignment.

• *Cleaner blade*

Before the tape reaches the head, as it comes out of the cartridge, it passes over a cleaner-blade assembly whose function is to scrape debris from the surface of the tape and to "vacuum" it away. The assembly used is the same as that used in the 3420 tape drive. It consists of two nonmagnetic carbide blades, one that is effective when the tape is moving forward and the other when the tape is moving backward. Vacuum is applied between the blades to hold the tape against the blades and draw off any debris. The assembly also acts as a channel guide as the tape enters the head-guide assembly.

• *Tape lifter*

To control the drag in the tape path, it is essential to prevent physical contact between the head and the tape at all times. When the drive is running, the tape flies over the read/write head with a hydrodynamic air-bearing. When the drive stops, the contact is minimized by the use of a pneumatic tape lifter [22]. The tape lifter is controlled by a solenoid valve that is activated at all times except during tape read and write operations. The hydrodynamic-bearing design provides slots on the head which prevent 100% lift-off with the hydrostatic air-bearing of the tape lifter. Although the remaining contact area results in a small dependency on the tape characteristics, the friction force is well within the range that can be handled by the drive.

There is a time delay in lifting and dropping the tape. The tape drop response time is an essential parameter that could potentially limit the access time of the tape drive. It is measured from the time at which the tape lifter is logically turned off to the time at which the tape is readable at the magnetic head, and is kept to a minimum through optimal design of both the pneumatic and the electronic circuits. The length of hose from the solenoid valve to the head is reduced to a minimum, and the valve is vented to the atmosphere when the compressed air is turned off (see **Figure 10**). In the construction of the solenoid valve, the lifting time is much more predictable than the drop time. The drop time of the solenoid, which is critical, depends on the efficiency of the magnetic circuitry and the mechanical tolerance of the valve position.

Tension transducer

The nominal tape tension is set open-loop by the microcode of the tape-transport electronics. Tension transients are controlled by a feedback loop. The tape tension is sensed by the tension transducer shown in **Figure 11**, whose position in the tape path can be seen in Figure 1, adjacent to the take-up reel. Its output is fed through a filter which compensates for the mechanical resonances of the system. This filtered tension signal is then applied differentially to the reel motors through the motor drivers.

The tension transducer is a hydrostatic air-bearing with a radius of 15 mm. The tape has approximately 180° of wrap on the bearing. A solid-state pressure transducer is used to sense tape tension by sensing the air pressure between the moving tape and the fixed surface of the air bearing through a sensor hole in the center of its face. The sensor hole is kept clean of debris by a constant air purge.

The assembly requires a simple adjustment for achievement of a null and provides accurate over- and under-tension limit sensing when used with a common bipolar window-detection circuit. It protects the drive from excessive tape-tension conditions, which could damage the tape or the head. The vented flanges stabilize the air-bearing and are used to prevent tape vibration that would degrade read/write performance. They also provide positive tape guiding between the head-guide assembly and the reel.

Summary

This paper has dealt mainly with the mechanical design aspects of the development of the 3480 tape drive. A precision tape threader eliminated the need for a two-reel cassette in favor of a low-cost, single-reel cartridge. A substantial increase in data density permitted the design of a compact cartridge, which reduced associated electrical power and library space requirements. Achievements associated with the single-reel cartridge included improved tape guiding through the use of air-bearings and compliant guides; improved tape tension control through use of a combination of drive microcode and pneumatically measured tape tension; and improved magnetic head isolation from staggered wraps through use of a decoupler.

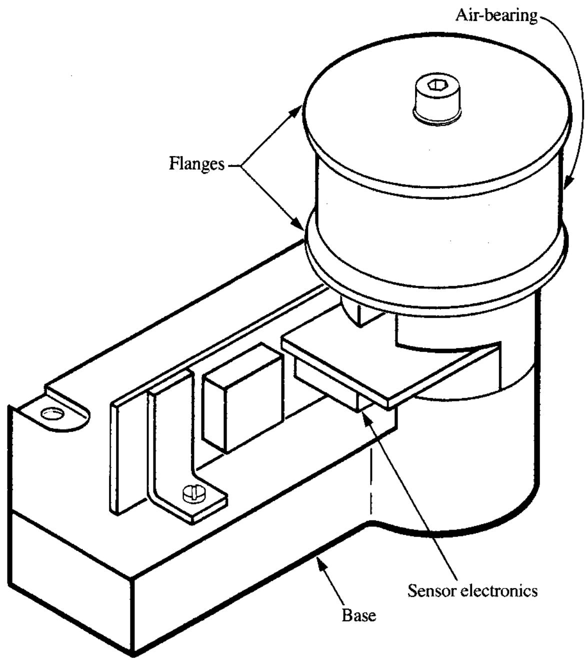

Figure 11

Tension transducer.

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