Use of Ceramics for Tape Guiding in the IBM 3480 Tape Path

Daniel J. Winarski
IBM Corporation, Tucson, AZ 85744

The IBM 3480 Magnetic Tape Subsystem uses a reel-to-reel tape transport to move 12.65 mm chromium dioxide tape across an 18 track, thin film head. The initial 3480 tape path uses 316 stainless steel both for compliant tape guides and reference guiding flanges. These steel guides quickly showed extreme wear, which resulted in shear vibrations in the magnetic tape during read and write operations. Alumina ceramic compliant tape guides and reference guides were used to resolve this wear problem. A strong recording velocity dependency resulted in different ceramic compliant tape guides for the 3480 Model B22 (2 m/s) and 3480 Model B11 (1 m/s).

INTRODUCTION

The IBM 3480 was IBM's second reel-to-reel tape drive (see Fig. 1.) To achieve a high recording density, the IBM 3480 used chromium dioxide tape (Bradshaw *et al.*, 1986). In order to meet the demands of guiding tape over an 18 track head, the IBM 3480 tape path needed compliant tape guides to seat the half-inch tape against a reference flange. Figure 2 shows that the initial 3480 tape path had compliant guides made from 0.1-mm-thick 316 stainless steel (Winarski *et al.*, 1986). These steel compliant guides seated the tape against 1-mm-thick reference lower flanges which were also made of 316 stainless steel. Figure 2 also shows that the lower flanges were vented (Andresen *et al.*, 1984) to allow for air escape from the hydrostatic air bearings, called D-bearings.

Eventually, the 3480 family of tape drives had to use alumina ceramic compliant guides and lower flanges to reliably guide the magnetic tape across the magnetic head. The 3480 Model B22 used alumina ceramic pads on the ends of stainless steel leaf springs as a compliant tape guide. The 3480 Model B11 used the same alumina ceramic pads on the ends of stainless steel plugs, enabling gravity to exert a guiding force on the upper edge of the tape. This article explains the reasons for these design choices.

HISTORICAL BACKGROUND

The means of guiding tape used on the 3480 is best understood by reviewing the means of tape guiding used on the older IBM tape drives, as shown in Table 1.

In 1979, IBM delivered its first 8809 tape drive (Harris *et al.*, 1981). IBM's first reel-to-reel tape drive, the 8809, used open channel tape guides made from tungsten carbide to control 12.65 mm iron oxide tape (ANSI, 1973). These open channel guides offered

Manuscript received November 20, 1990; revised manuscript received January 4, 1991.
Contributed by the Tribology Division of the American Society of Mechanical Engineers.

Adv. Info. Storage Syst., Vol. 1, 1991, ISSN 1053-184X, ISBN 0-7918-0021-0

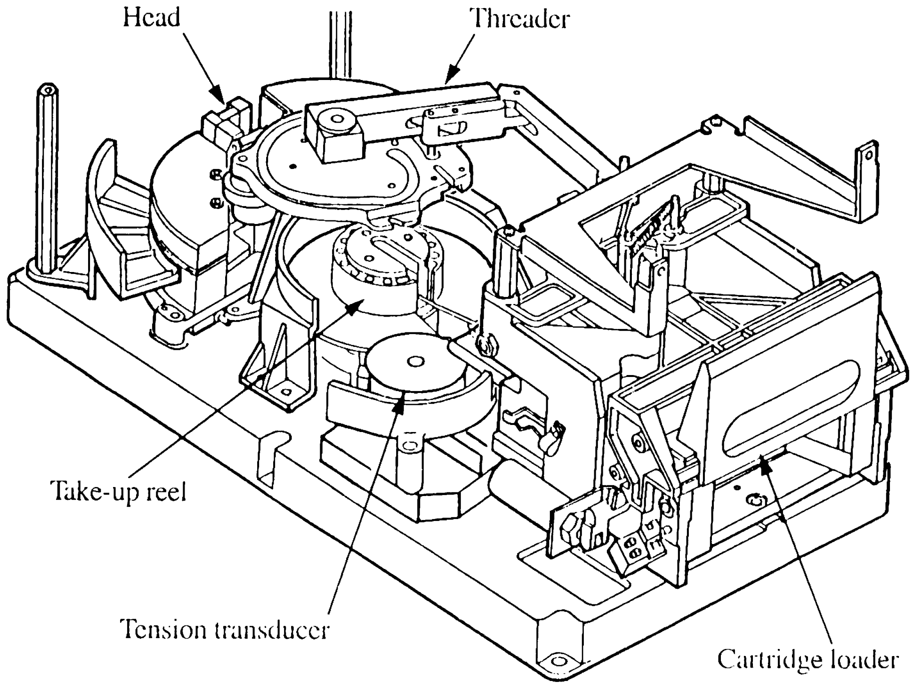

FIG. 1. Tape path of the IBM 3480.

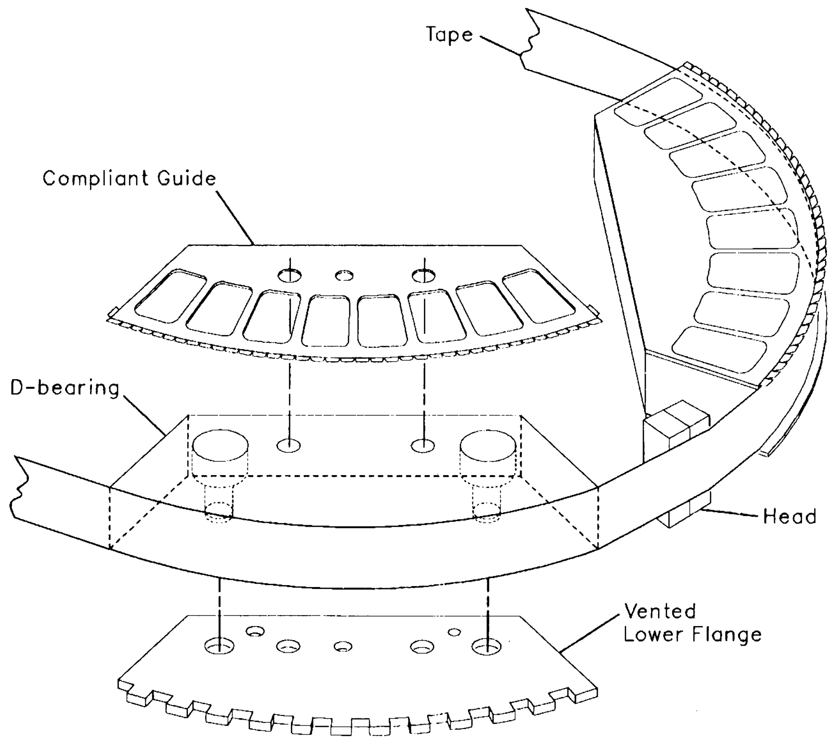

FIG. 2. Initial stainless steel compliant guides for the IBM 3480.

Table 1. Summary of tape drives

Tape unit	Tape width (mm)	Track layout	Tape velocity during actual data transfer (m/s)	Maximum data rate (bytes/s)	Year
726	12.65	7 track	1.9	7,500	1953
729-III	12.65	7 track	2.8	62,550	1958
2401-6	12.65	9 track	2.8	180,000	1966
3420-8	12.65	9 track	5.0	1,250,000	1973
3850	68.58	Diagonal	0	374,000	1975
8809	12.65	9 track	2.5	160,000	1979
3480-B22	12.65	18 track	2.0	3,000,000	1984

no constraint on the tape until the tape pressed against the guides themselves. The tape was wrapped 0.17 rad (10°) across the hydrodynamically lubricated guide blocks. Figure 3 shows this means of guiding.

The IBM 3420 also employed open channel guides made from tungsten carbide, as shown in Fig. 4. During normal drive operation, the tape was not expected to contact either flange of the open channel system. Only during large lateral displacements could

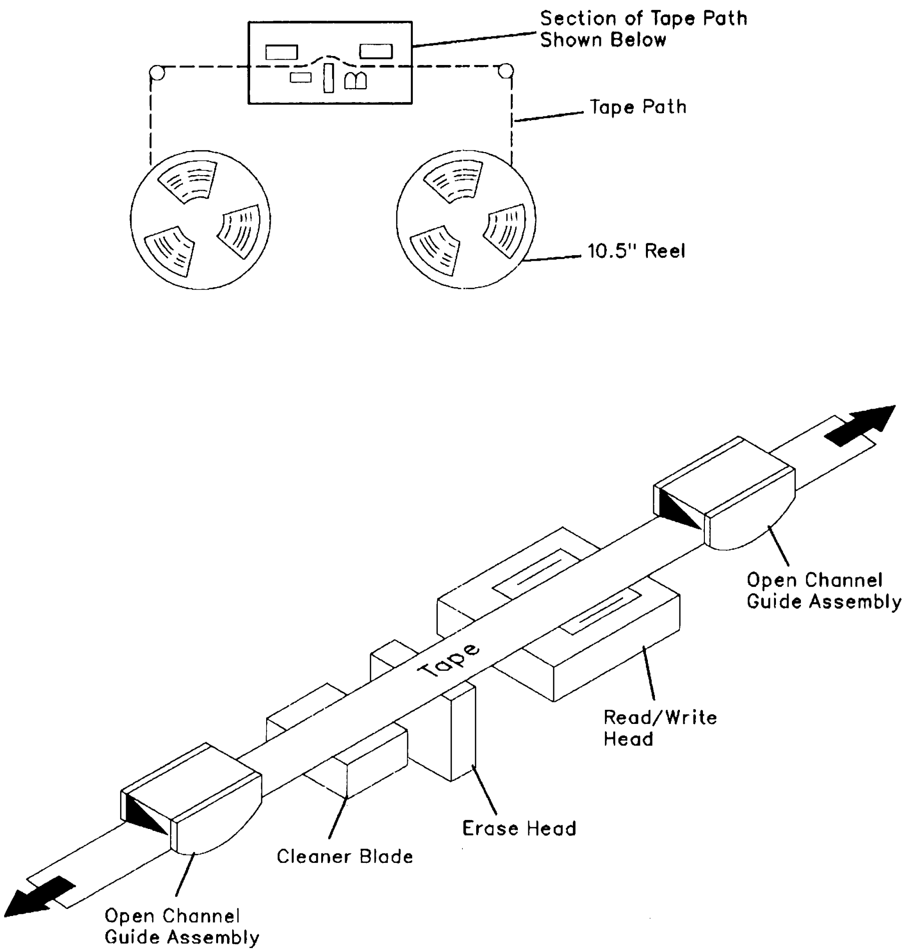

FIG. 3. Tape guiding for the IBM 8809.

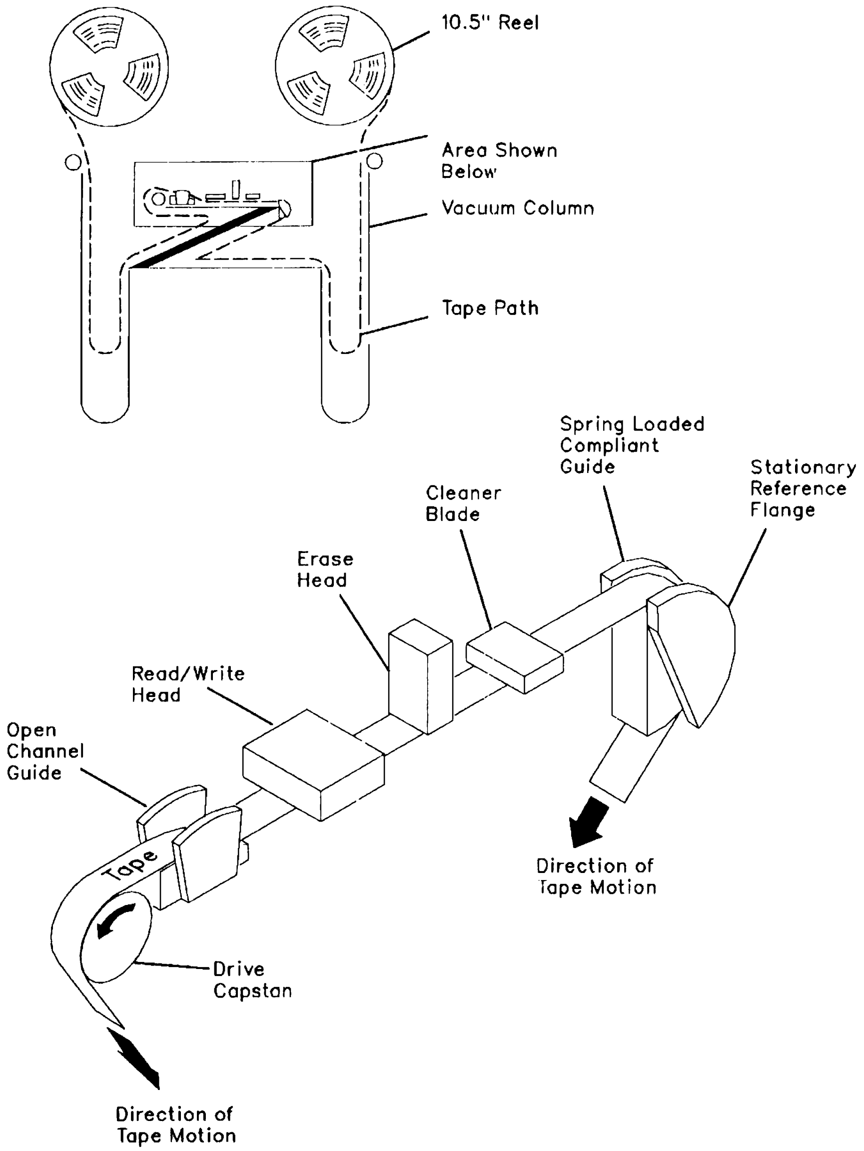

FIG. 4. Tape guiding for the IBM 3420.

the tape come in contact with the flanges of the open channel guides. More about the IBM 3803/3420 Magnetic Tape Subsystem can be found in Irwin *et al.* (1971).

The IBM 2401 used circular cylinders as hydrodynamically lubricated guide blocks. These guide cylinders were 25.4 mm in diameter. One flange on each cylinder was a spring-loaded alumina ceramic flange. This ceramic flange seated the magnetic tape against another alumina reference flange on the opposite end of the guide cylinder, as shown in Fig. 5. The equivalent load on the tape from each spring loaded alumina ceramic flange was 100 g. Prolays, which were first used in the IBM 729 Model III, moved pinch rollers to engage the tape to capstans. The IBM 2401 had a substantially improved data rate over the 7.5 KB/s of the IBM 726 drive.

In 1975, the IBM 3850 Mass Storage System was shipped to customers (Harris *et al.*, 1975). IBM's 3850 tape library employed 302 stainless steel compliant guides and hy-

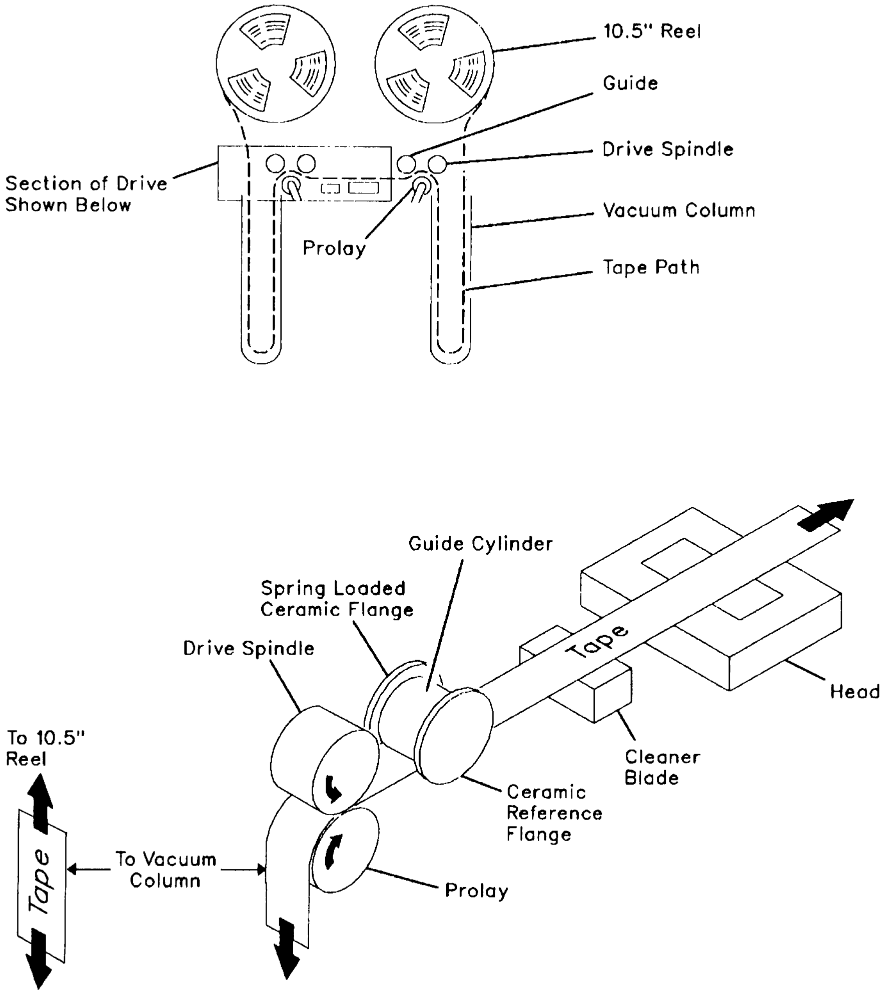

FIG. 5. Tape guiding for the IBM 2401.

drostatic air bearings. The compliant guides seated the 68-mm-wide iron oxide tape against reference guides made from 316 stainless steel. The 3850 also used formatted media to assist in the location of data areas. The IBM 3480 did not use formatted media.

The first prototype of the IBM 3480 attempted to use the same type of open channel guides as the 8809. However, the open channel guides failed to control the tape within the allotted lateral and skew guiding limits. The hydrodynamic guides did not function effectively, especially when the tape was accelerating at 100 m/s^2 from a standstill while in a hot and wet environment.

The tape guiding scheme for the 3480 was then changed to one similar to the 3850. On both sides of the 18 track head, compliant tape guides made from 316 stainless steel were placed (Winarski *et al.*, 1986). The reference lower flanges were made of 316 stainless steel as well. Like the 3850, hydrostatic air bearings were used instead of 8809-like hydrodynamic air bearings. The 3480 hydrostatic air bearings were designed with approximately 1.5 rad of wrap each and were also used on each side of the head.

The use of stainless steel for the compliant tape guides and lower flanges was not seen as a problem during the initial testing of the 3480. A frequently used matrix of test cartridges was kept throughout the testing. This meant that the edges of the chromium dioxide tape were eventually smoothed to some extent. The wear problem, which would result from continual use of freshly slit chromium dioxide tape, would not be seen until a second battery of tests.

In the second battery of tests, cartridges were being used to archive data. Rather than a frequently used small matrix of test cartridges, large amounts of cartridges were available and a large number of cartridges were processed daily. Individually, these cartridges were typically read or written infrequently, approximately monthly. This meant that the 316 stainless steel guides saw the edges of a great deal of freshly slit, abrasive chromium dioxide tape. The compliant guides and lower reference flanges wore quickly, resulting in 50 and 100 kHz shear waves in the magnetic tape. An example of a wear groove profile can be found in Bhushan's article (1987).

The 3850 escaped this wear problem for two reasons. First of all, iron oxide tape is much less abrasive against stainless steel than chromium dioxide tape (Bhushan, 1987). Second, the tape was not moving during reading or writing on the 3850, thus, the tape was not being excited by rubbing against wear scars.

ANALYSES OF SHEAR WAVES

Rapid wear of the 316 stainless steel compliant guide seen in Fig. 2 resulted in shear waves in the magnetic tape run on 3480 drives. There were two mode shapes associated with these shear waves, as seen in Fig. 6. At 50 kHz, the amplitude of the wave varied

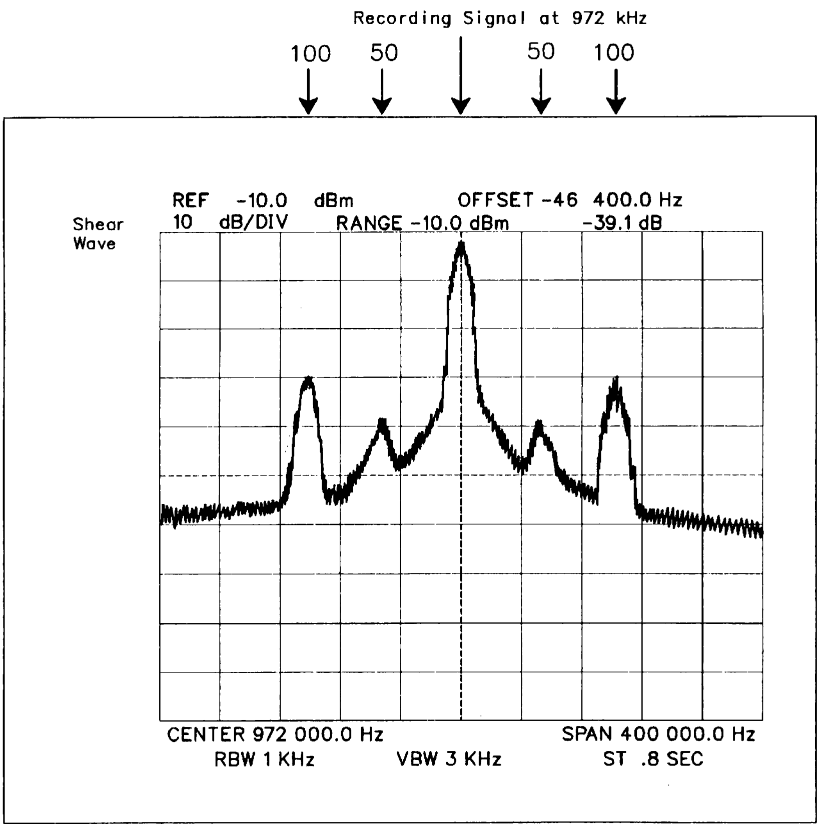

FIG. 6. Fifty and 100 kHz shear waves with stainless steel guides.

linearly across the width of the tape, with a node at the centerline of the tape. This mode shape was consistent with one edge of the tape being excited by a wear scar. At 100 kHz, the amplitude of the wave had a triangular profile, with two nodes each halfway between the centerline of the tape and the outer edges. This second mode shape was consistent with both edges of the tape simultaneously being excited by wear scars in the compliant guide and lower reference flange. These shear waves affected data reliability, because their direction of oscillation was parallel to the direction in which data was recorded.

The 50 and 100 kHz shear waves were modeled by integrating the following second-order partial differential (Eringen, 1967):

$$a^2\left(\frac{d^2u}{dy^2}\right) = \frac{d^2u}{dt^2} \tag{1}$$

where a equals $\sqrt{G/\rho}$; G is the shear modulus of the tape (2.4 GPa); ρ is the mass density of the tape (1500 kg/m^3); u is the longitudinal displacement in the elastic tape; y is the coordinate along the width of tape; and t is time. The boundary conditions were that the reels of tape were so far away that the ends of tape were essentially free and that the edges of the tape were free to oscillate.

The eigenvalue for the first shear wave is given by Eq. (2); the second shear wave is given by Eq. (3).

$$Q(50) = \frac{1}{2w}\sqrt{\frac{G}{\rho}} = 50 \text{ kHz} \tag{2}$$

$$Q(100) = \frac{1}{w}\sqrt{\frac{G}{\rho}} = 100 \text{ kHz} \tag{3}$$

where Q is the shear eigenvalue and w is the width of tape (12.65 mm). The associated frequencies and mode shapes were empirically verified by looking at the amplitudes and phase relationships across the 18 tracks of all ones data patterns. After the worn stainless steel compliant guides were replaced with the ceramic guides shown in Fig. 7, the amplitudes of both of these shear waves went to zero.

USE OF CERAMIC GUIDES ON THE 3480 MODEL B22

The compliant tape guide used on the 3480 Model B22 consisted of eight alumina ceramic pads, each at the end of a stainless steel leaf spring (Garcia and Koloseus, 1986). The composite edge load of these eight pads was sufficient to guide tape within the required lateral and skew limits. The data reliability of the 3480 Model B22 greatly improved because of the change to ceramic tape guides adjacent to the magnetic head. The lower reference flanges on the 3480 were also changed from stainless steel to alumina ceramic. This was to prevent eventual loss of registration of the lower edge of tape with respect to the lower track of the 18 track head. The geometry of the lower reference flange was not changed by this change in material.

After the 3480 Model B22, a 2 m/s tape drive, IBM pursued the 3480 Model B11. The Model B11 was a 1 m/s drive which offered half the burst data rate of the B22. This slower speed tape drive offered new challenges in tape guiding in order to reduce longitudinal vibrations in the magnetic tape.

ANALYSES OF LONGITUDINAL WAVES

The IBM 3480 Model B22 had a 15 db safety margin with respect to tape vibrations. However, the acceleration limit in a tape path is a function of the square of the tape

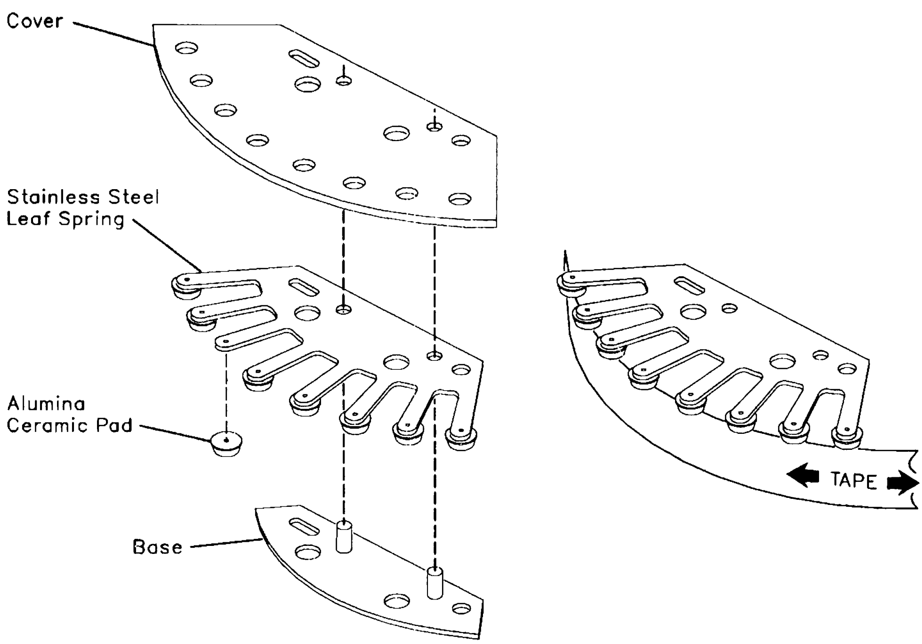

FIG. 7. Ceramic guides for the IBM 3480 Model B22.

velocity, as given in Eq. (4). In Eq. (4), acceleration is defined to be the second derivative of the longitudinal displacement in the tape, u. The higher the acceleration d^2u/dt^2 in the tape, the lower the signal to noise ratio.

$$\text{Maximum acceleration } \left(\frac{d^2u}{dt^2}\right) \text{ limit} = P * D * V^2 \tag{4}$$

where P is the allowable tolerance on the flux change (fc) density [0.0005/ bit = 1.6%/32 fc (Proposed American National Standard)]; D is the IBM 3480 density [972,000 fc/m (Proposed American National Standard)]; and V is the tape operating velocity in m/s.

Equation (4) is derived by defining the maximum permissible longitudinal acceleration as the quotient of a 0.05% change in velocity divided by the time for one flux change. This derivation is shown for the IBM 3480 in Eq. (5).

$$\text{Maximum acceleration } \left(\frac{d^2u}{dt^2}\right) \text{ limit} = \frac{0.0005\ V}{\text{time for 1 flux change}}$$

$$= \frac{0.0005\ V}{\dfrac{1}{(D * V)}} = 0.0005 * D * V^2 \tag{5}$$

When shifting the design point of the recording velocity from 2 to 1 m/s, the maximum permissible acceleration decreased by a factor of 4. The ceramic compliant guide which had been found acceptable for the 3480 Model B22, as seen in Fig. 7, was suddenly unacceptable for the 3480 Model B11. The problem with the 3480 Model B22 ceramic compliant guides at 1 m/s was that the tape became excited in several longitudinal modes of vibration. These longitudinal modes of vibration were excited by an interaction between the tape and the ceramic pads caused by the elasticity of the leaf springs in the direction which was parallel to the motion of the tape.

These longitudinal waves were modeled by integrating the following second-order partial differential equation (Eringen, 1967).

$$b^2\left(\frac{d^2u}{dx^2}\right) = \frac{d^2u}{dt^2} \tag{6}$$

where b equals $\sqrt{E/\rho}$; E is the Young's modulus of the tape (4.9 GPa); and x is the coordinate along the length of the tape. The boundary conditions were that the reels of tape were fixed boundaries and the ends of tape, that is, $u(0, t)$ and $u(L, t)$, were zero.

The eigenvalues for the longitudinal waves are given by Eq. (7). The fixed boundary conditions at each end of tape result in only odd harmonics of the fundamental frequency.

$$R_i = \frac{2i - 1}{2L}\sqrt{\frac{E}{\rho}} \tag{7}$$

where R_i is the longitudinal eigenvalue and L is the length of tape in the tape path (0.6 m). From Eq. (6), the first theoretical eigenvalue was at 1.5 kHz. Subsequent theoretical eigenvalues were odd harmonics: 4.5, 7.5, 10.5, 13.5, and 16.5 kHz.

The sets of 1.5 to 16.5 kHz longitudinal waves were seen in the 3480 Model B11 tape path when using the ceramic tape guides already in use for the 3480 Model B22, as shown in Fig. 8. This empirical measurement was obtained by differentiating the signal read from

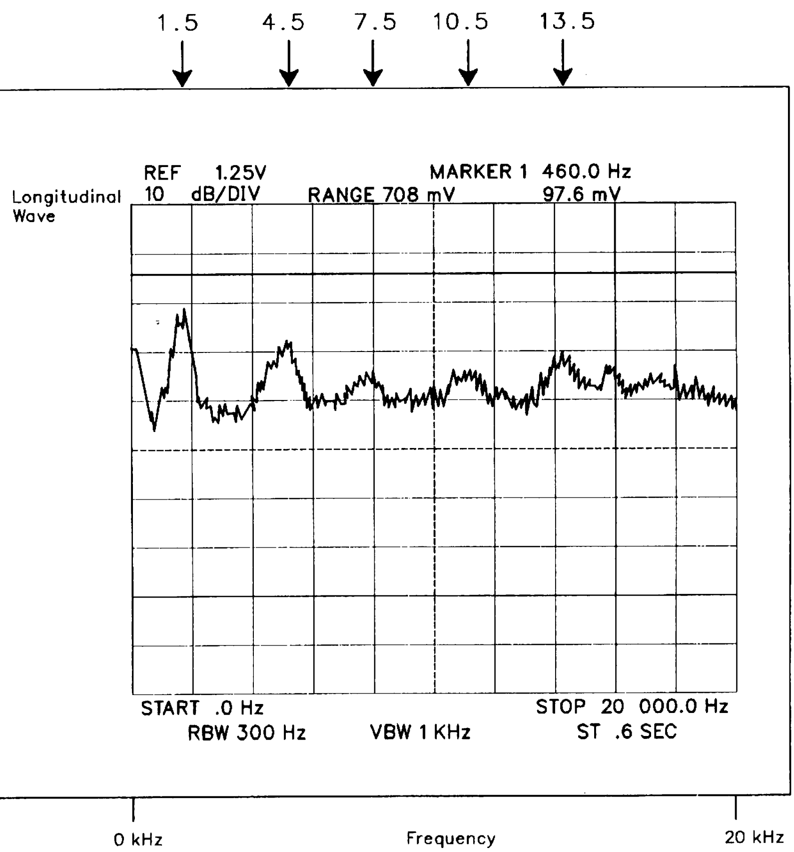

FIG. 8. Longitudinal waves at 1 m/s with 3480 B22 compliant guides.

a tape written with an all ones data pattern. Damping within the tape prevented longitudinal frequencies higher than 16.5 kHz. The composite effect of all of these active longitudinal modes of vibration exceeded the allowable tape acceleration budget for the 3480 Model B11. A new type of ceramic tape guide was needed.

USE OF CERAMIC GUIDES ON THE 3480 MODEL B11

The solution for the 3480 Model B11 compliant tape guides was to use stainless steel cylinders tipped with the same ceramic pads used on the 3480 Model B22 compliant guide (Corradini *et al.*, 1988). Figure 9 shows an exploded view of this design. The mass of each stainless steel cylinder was 2.5 g, and three such cylinders were used per guide, as also shown in Fig. 9. This gave 7.5 g of hold-down per guide, which was more than adequate.

Because the stainless steel cylinders did not have the elasticity inherent in the ceramic tipped leaf springs used in the 3480 Model B22, the tape was not excited in the longitudinal direction at high frequency. There was still some component of the 1.5 kHz fundamental frequency after implementation of the new guides for the 3480 Model B11. However, the amplitude of this fundamental frequency was minimized by tuning the compliant guides to the tape path. This was done by having two 2.5 g cylinders near the head and one cylinder at the opposite side of each guide. This tuning allowed the 3480 Model B11 to meet its acceleration specification Eq. (4) at its 1 m/s operating velocity. Because the guides for the 3480 Model B11 were not identical, tabs were put on the guides to prevent improper assembly in the manufacturing process. Figure 9 shows these tabs.

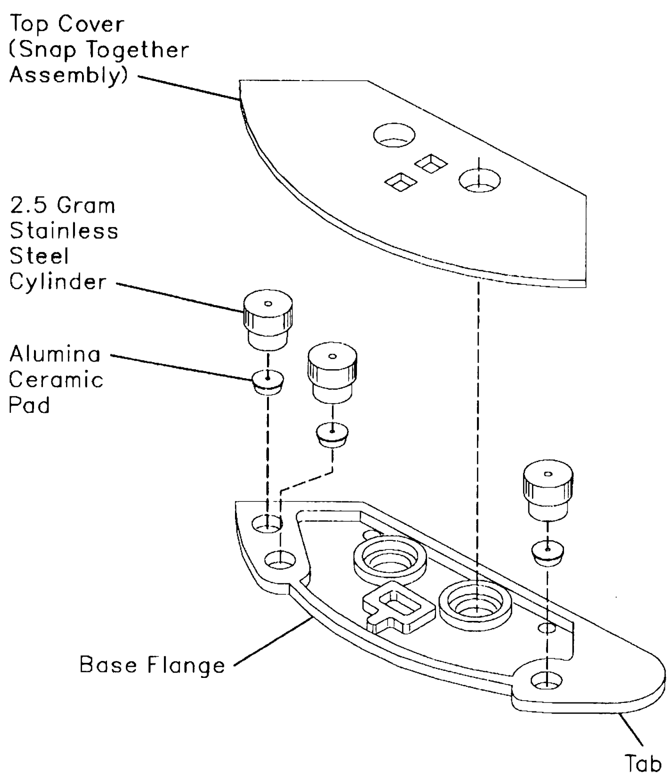

FIG. 9. Ceramic guides for the IBM 3480 Model B11.

CONCLUSIONS

Use of ceramic tape guides adjacent to the 18 track head enabled the 3480 to reliably guide tape. The evidence for placing ceramic guides in the IBM 3480 was gathered from 3480 transports and from test fixtures (Bhushan, 1987). There were two compliant guides, one on each side of the head. For both 3480 Models B22 and B11, the lower reference flange was made of alumina ceramic. The compliant guides varied between the 2 m/s 3480 Model B22 and the 1 m/s 3480 Model B11.

The 3480 Model B22 used alumina ceramic pads at the ends of stainless steel leaf springs. This design gave a 15 db safety margin on tape acceleration at 2 m/s. However, at 1 m/s, the allowable tape acceleration decreased by a factor of 4 (12 db). This necessitated the design of a different compliant guide, one where the mass of ceramic tipped stainless steel plugs seated the magnetic tape against the reference lower flanges.

ACKNOWLEDGMENTS

The author would like to acknowledge the efforts of B. Bhushan, W. W. Chow, L. W. Curtis, J. A. Dalmas, J. L. Garcia, B. G. Lott, J. A. McDowell, C. L. Murphy, and R. K. Rhodes of IBM Corporation.

REFERENCES

"American National Standard: Unrecorded Magnetic Tape for Information Interchange (9-Track 200 and 800 CPI, NRZI, and 1600 CPI, PE)," American National Standards Institute, Inc., New York, NY, ANSI X3.40–1973, 9.

Andresen, R., Bareman, P. R., Garcia, J. L., and Guzman, A. M. (1984), "Tape Guide Design," *IBM Tech. Discl. Bull.*, **27**, 4360–4361.

Bhushan, B. (1987), "Development of a Wear Test Apparatus for Screening Bearing-Flange Materials in Computer Tape Drives," *ASLE Trans.*, **30**, 187–195.

Bradshaw, R. L., Bhushan, B., Kalthoff, C. H., and Warne, M. D. (1986), "Chemical and Mechanical Performance of Flexible Magnetic Tape Containing Chromium Dioxide," *IBM J. Res. Dev.*, **30**, 203–216.

Corradini, J. A., Garcia, J. L., Koloseus, J. C., Lenart, C. A., Rhodes, R. K., Smith, K. L., and Winarski, D. J. (1988), "Tape Guide Assemblies with Weighted Buttons," *IBM Tech. Discl. Bull.*, **31**(3), 232–233.

Eringen, A. C. (1967), *Mechanics of Continua,* John Wiley and Sons, Inc., New York, NY, 104.

Garcia, J. L. and Koloseus, J. C. (1986), "Compliant Guide Assembly with High Wear Resistance Contact Pads," *IBM Tech. Discl. Bull.*, **29**, 2126–2127.

Harris, J. P., Phillips, W. B., Wells, J. F., and Winger, W. D. (1981), "Innovations in the Design of Magnetic Tape Subsystems," *IBM J. Res. Dev.*, **25**, 691–699.

Harris, J. P., Rhode, R. S., and Arter, N. K. (1975), "The IBM 3850 Mass Storage System: Design Aspects," *Proc. IEEE*, **63**, 1171–1176.

Irwin, J. W., Cassie, J. V., Oppeboen, H. C. (1971), "The IBM 3803/3420 Magnetic Tape Subsystem," *IBM J. Res. Dev.*, **15**, 391–400.

"Proposed American National Standard: Magnetic Tape and Cartridge for Information Interchange 18-Track, Parallel, 12.65 mm (1/2 in), 1491 cpmm (37871 cpi) Group-Coded Recording." American National Standards Institute, Inc., New York, NY, ASC X3 Project No. 487/488, 15 May 1988.

Winarski, D. W., Chow, W. W., Bullock, J. G., Froehlich, F. B., Osterday, T. G. (1986), "Mechanical Design of the Cartridge and Transport for the IBM 3480 Magnetic Tape Subsystem," *IBM J. Res. Dev.*, **30**, 635–643.