A Comparison of Rotary- and Stationary-Head Tape Recorders

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Abstract

Digital recording may take advantage of many types of media, but usually a preferred type of drive or transport emerges for each. In magnetic tape recording, two approaches have emerged in which essentially the same medium is tracked in two radically different ways. This paper compares the characteristics of Rotary- and Stationary-Head transports in an attempt to establish which approach might be considered for a given application. The conclusion is that in many cases there is no obvious choice based on recording physics and that often the choice will be made on the experiential knowledge of the designer.

The Limits of Tape Recording

This paper restricts itself to digital recording, but in practice a tape transport does not know the meaning of waveforms passing through its heads and media. These waveforms experience an analog channel which has suboptimal frequency response as well as non-linearities and various noise mechanisms. It is the discrete decision-making process of the replay data separator which renders the entire machine digital. The channel coder in the record section merely produces waveforms which are advantageous to a discrete data separator. The impairments of the real channel result in a certain error rate distribution and a suitable error correction strategy will be employed in order to meet the residual BER demanded by the application.

Assuming an acceptable BER, tape-based data recorders are measured by the following primary parameters: Unit cost, maintenance cost, cost per bit stored, transport and medium size and weight, access time and transfer rate. Secondary parameters are figures which are only critical in certain applications. These include environmental tolerance, power consumption, speed range, startup time and so on. The storage density emerges as a critical factor as an improvement allows the same job to be performed with a smaller, lighter machine at a lower cost per bit. Storage density improves by paying attention to three dimensions. Thinner tape allows a greater surface area in a given volume and allows better conformity with the head. It does, however, require a substrate with higher tensile strength and more precision in the tension control system of the transport. A reduced track pitch increases density but requires a more accurate track-following mechanism, improved means to reject crosstalk and a higher output medium to restore the noise performance. Reduced bit-length along the track is the third dimension and demands heads with smaller gaps, better head/tape contact, higher output media and channel codes with improved figures of merit. In general an increase in density will raise the raw BER and require a more powerful error correction strategy.

An improvement in superficial (or areal) density reduces access time as a shorter tape holds the same data. Smaller reels have lower inertia and withstand harsh acceleration environments better. The linear (along-track) density is primarily determined by magnetics and coding, whereas the cross-track density is primarily limited by tracking accuracy which is mechanically determined.

Mechanical Considerations

The above criteria can now be examined from the alternative viewpoints of stationary and rotary head implementations. [Reference 1].

As tracks of the order of 10 micrometers wide are in use today, clearly a single track tape is a mechanical impossibility. A stationary head recorder will as a practical matter need to use a significant number of parallel tracks across the tape and the bit rate will be divided between them. These tracks will be recorded and played by multi-track head stacks. High density machines will need active track following mechanisms physically to move the headstack in compensation for tape weave, typically using piezo-electric or magnetostrictive "muscles".

The track width and pitch are fixed and are determined by the head design. Crosstalk in the form of mutual inductance may take place between the various magnetic circuits in the headstack and this must be controlled by the introduction of spaces and/or shields between the magnetic circuits which result in guard bands between the tracks. Photolithograpically produced heads are better from the standpoint of mutual inductance because of their flat construction, but spaces between the tracks are still inevitable because of the need to arrange windings around the poles.

As an alternative interleaved headstacks may be made in which only one in N tape tracks is furnished with a magnetic circuit. Depending on the bit rate required, the transport may have N headstacks or may transport the tape N times through the machine in a serpentine fashion, indexing the headstack to one of N places on each pass. If N headstacks are used, each must have its own track following actuator. A serpentine recorder needs only one headstack actuator, but its travel will be much longer.

To record the same bit rate, the rotary head recorder produces a large number of slant tracks by the rapid rotation of a small number of heads. These tracks can be nearly perpendicular to the tape motion in transverse scan recorders or nearly parallel to the tape motion in helical scan recorders. In both cases the tracking mechanism relies upon the cross-track component of tape linear motion which can thus be controlled by capstan phase. The track pitch is controlled by the linear tape speed and is independent of the dimensions of the head. It is possible to have a machine which supports more than one track pitch so that, for example, tapes of various coercivities can be used. The heads on a rotary scanner are not in a stack, but are distributed around the periphery so that mutual inductance effects are negligible. Rotary transformers are required to couple the rotating signals with the stationary signal processing circuitry and these will be prone to crosstalk, although modern multi-head machines have rotating pre-amplifier circuitry so that the transformers do not handle signals direct from the replay heads.

We can say that a rotary head recorder is no more than a mechanical multiplexer which lays down tracks rapidly with few heads whereas a stationary head recorder lays the tracks down slowly with many heads. We could well use the analogy of serial and parallel transmission. Both approaches require active track following at high density. The stationary head transport does this by moving the head whereas the rotary head machine moves the tape. Thus the common criticism that rotary head machines are complex is not so strong at high densities where a stationary head transport needs a track following servo, or with interleaved heads, several servos.

Capstan phase control in rotary head recorders cannot accommodate track straightness errors due to, for example, interchange inaccuracies. In this case, the rotating heads may have an additional track following mechanism which allows the heads to be deflected along the scanner axis (i.e transversely with respect to the tape track) as the scanner rotates. In this case geometric errors within the track can be compensated. In a rotary head recorder the head/tape interface is complex. The revolving scanner builds up an air film and the film thickness stabilizes when the tape tension balances the air pressure. This is one reason why tape tension is critical in rotary head recorders. As a result of the air film the scanner itself does not touch the tape and friction around it is very low. The head pole must project out of the scanner by a distance equal to the film thickness plus an amount needed to deform the tape to give the required contact pressure. The traveling deformity in the tape results in acoustic noise which may need attenuation in some applications. The linear speed of the head with respect to the tape must be kept below the propagation speed in the tape to avoid the creation of mechanical shock waves which result in rapid wear. At the relative speeds involved, there is appreciable aerodynamic lift attempting to separate the head and the tape. The conditions are in a region midway between the firm contact of a slow speed stationary head tape and the non-contact system of a hard disk. The wear reducing properties of the lift can be balanced against separation loss. In practice head wear is greater on new tapes where asperities are linished by the heads. Older tapes show reduced head wear and error rates.

Head Design

Naturally rotary heads experience high frequencies and the magnetic circuit must be constructed is such a way that eddy current losses are minimized. Ferrite is non conductive but saturates before today's high coercivity tapes can be fully modulated. Metal pole tips can be fitted to ferrite bodies, or lamination or sintering can be used to raise head resistivity. A single head may reach 200 megabits/second, but in practice lower figures are used for other reasons such as the need to distribute data over several heads to give resistance to clogging or to reduce the frequency at which the associated circuitry must operate. Whilst the reading speed has no effect on most types of noise, raising the speed does increase the replay signal in proportion and so the effect of head and preamplifier noise is reduced.

Conversely inductive heads are at a disadvantage at low relative speeds. For a given bit rate, stationary head, or parallel recording, implies low frequencies where magneto-resistive heads with their non-derivative action give a noise advantage. There is a changeover at approximately one megabit per second where the two types are roughly equal in performance. Thus in general rotary head recorders use inductive heads where eddy current losses are a concern whereas stationary head recorders will use magneto-resistive heads where eddy current losses are insignificant unless prodigious bit rates are envisaged.

Apart from the requirement for the appropriate magnetic orientation for transverse scan, there is little difference in the magnetics between tape intended for rotary and for stationary head machines. Therefore any development in tape technology is available to both. Similarly developments in channel coding and signal processing are also available to both. Rotary head recorders require smaller DC components in channel codes due to the presence of the rotary transformers, although in practice both types of machine have been seen with the same channel code. Similarly techniques such as partial response are equally applicable.

In error correction, stationary head recorders see defects in several tracks simultaneously and need to interleave by distributing codewords over several heads to restrict their impact. Rotary head recorders to an extent interleave mechanically as a circular dropout appears as a spaced out series of defects in successive head scans.

One significant difference between serial and parallel recording is that the rotary head recorder is naturally complemented by the adoption of azimuth recording. Rotary head transports have a small number of heads and these are spaced apart physically. It is easy to make such heads (minimum two) with alternating azimuth angles. If a suitable channel code is employed to restrict the ratio of maximum and minimum wavelengths, erasure by overwrite can be employed. Not only does this eliminate the erase head, it allows the track width to be determined by the tape speed and not the head design. If the poles of the record head are made wider than the track pitch, part of the side of a given track will be erased by the next track to be written. Azimuth effect allows replay heads to read these adjacent tracks despite the lack of a guard band. As a result azimuth recording has come to be synonymous with the term guard-band-less recording.

Tapes of different coercivity can be handled by choosing an appropriate track width and driving the tape at a suitable linear speed. This approach is used in RDAT which can operate with 13 micrometer tracks on metal particle tape but which uses 20 micrometer tracks on barium ferrite tape which is required for contact duplication.

In principle certain aspects of azimuth recording can be used with stationary heads, and such devices are known if uncommon. In one implementation, two interleaved headstacks are used, one of each azimuth type. The first head writes tracks which are oversized, and the second writes tracks of the correct width between the others, side trimming them to size by overwrite. In practice it is difficult to fabricate multitrack heads with azimuth angles other than 90 degrees. This applies to conventional heads as well as those which are fabricated using photolithography.

Variable Speed

The different transport designs react differently to the requirement to operate at variable speed. It is necessary to be quite precise about the kind of variable speed operation being considered. In instrumentation, variable speed operation implies that the timebase of the recording and reproduce processes is different, but all of the data are fully recovered. This allows, for example, the high data rate of a practical experiment to be recorded as it occurs, but reproduced at a rate appropriate for the analysis process, which may well have a restriction such as the I/O speed of a computer. A linescan recording from a high speed airplane may be studied at leisure on a display.

On the other hand the requirement in a digital video recorder is only that a recognizable picture shall be available at non-standard speeds, and so a great deal of data can be lost.
In computation, the transfer rate of a given drive is usually fixed, but a variety of drives may be available, at different costs, which can offer different transfer rates on a common interchange medium.

In a stationary head recorder, the data rate from the heads is directly proportional to the tape speed. If a variable bit rate is required, then changing the tape speed will require a corresponding change in any record or reproduce equalization in every active track. In machines with a large number of tracks this becomes very complex. At high speeds the frequencies seen by the heads become very large. This precludes the use of stationary heads for production (as opposed to consumer) video recording. Although normal speed operation is perfectly feasible, high shuttle speeds (100x - 200x) cannot produce pictures.
Rotary head recorders are not capable of operating over a wide range of transfer rates where no data are lost. This is because the transport aerodynamics must be optimized for one speed. Changing the transfer rate requires the scanner and capstan to change speed by the same amount and this results in a significant change to the pumping effect of the scanner, with consequent changes to the air film thickness and tip penetration.

The helical scan recorder is advantageous for digital video recording because the tracks are nearly parallel to the tape edge. When the tape is driven linearly at the wrong speed, the scanner speed is not changed in proportion and so the tracking breaks down. Despite that it is possible to recover around 40% of data as heads cross tracks at a grazing angle. Provided the track crossing angle is sufficiently shallow, sync blocks on the track can be recovered and if they are uniquely addressed the data can be used to update a frame store. A further advantage of helical scan is that the head to tape speed is dominated by the scanner speed. As a result it is possible to maintain a reasonably constant head to tape speed over a wide linear tape speed range simply by modulating the scanner speed. The result is that the replay electronics will see constant frequencies and their data separators will operate normally.

The short tracks of the transverse scan recorder are almost at right angles to the tape motion and as a result the length of track recovered at shuttle speed is too small to allow sync blocks to be recovered. Thus the transverse scan machine is at a disadvantage for the production video recorder market where pictures in shuttle are mandatory.

Video recorders fitted with deflecting heads are capable of following entire tracks over a range of speeds typically from -1 to +3. When a helical scan transport records, the tape is wrapped around the scanner at the helix angle, which is determined by the construction of the scanner. However, the tape is moving as the scanner rotates, and the result is that the track angle differs from the helix angle. Thus variations in tape linear speed affect the effective track angle, and the head must be deflected by a ramp waveform to follow. The steepness of the ramp is proportional to the deviation from normal speed. It is possible to use the head deflection mechanism of a rotary head recorder to increase the proportion of data recovered during shuttle.

In instrumentation recording, incremental operation is becoming popular. In an incremental recorder, the transport and data channel are optimized for a single data rate, and all lower rates are implemented via a buffer memory which absorbs input data until the transport can run at speed and record a whole block. Similarly on replay data are output at any rate from the memory and the transport runs in bursts in order to keep the memory topped up. Incremental recording has been seen on stationary head, transverse and helical scan machines, but all are not equally suitable.

At bit rates near the maximum, the size of the memory is a function of the data rate and the time taken for the transport to change mode. At high density, it is not acceptable to leave IRGs (inter record gaps) in between increments. In practice, at the end of an increment the transport will cease writing, stop, reverse a short way and wait. On writing the next increment the transport will accelerate to speed (pre-roll) and read the end of its last increment so that the new data can be appended contiguously after the old in an assemble edit. This avoids the creation of a gap on the tape. However, the memory must be able to absorb virtually the full data rate for the time taken to reposition and pre-roll.

At bit rates well below maximum, the transport spends only a small proportion of time transferring data. The rest of the time it is idle or repositioning. An idle stationary head recorder does not suffer head wear as there is no relative motion. However, rotary head recorders must keep the scanner running in order to eliminate the lengthy acceleration period. There is thus a potential headwear problem which can only be avoided by unwrapping the tape from the scanner. The transport then enters a standby mode. The time taken to go between standby and functional modes must be added to the reposition time and so determines the memory capacity required at low speeds.

In helical scan, unwrapping is a complex process which requires the operation of several moving guides and which takes an appreciable time. On the other hand a transverse scan rotary head transport can be unwrapped simply by retracting the single cupped guide which conforms the tape to the scanner. This can be done in milliseconds with a solenoid. As a result the transverse scan rotary head transport finds itself at an advantage in the incremental recording application as smaller buffer memory is needed.

Size

Size means different things in different applications. In some cases it is the size of the tape reel or cassette which is important, especially if it needs to be shipped. On the other hand it may be that the overall size of the recorder is restricted, for example in airborne installations.

Tape cassettes are advantageous in that they protect the tape well from handling damage and require little skill to insert in the transport. However, cassettes are at a disadvantage for shipping because they are volumetrically inefficient. A cassette contains two reels, but when one is full, the other must be empty. As a result, instrumentation users will sometimes choose to retain open reels when really large quantities of data must be shipped on tape.

Where overall size matters, the choice of cassette or open reel becomes irrelevant as two reels are needed by both. The stationary head transport can be made very compactly as the head block takes up very little space. In contrast the scanner and threading mechanism in a helical scan transport will take up appreciable space, often making the deck area double that of the cassette. The transverse scan design is appreciably more compact as the headwheel has a much smaller diameter and the axis of rotation is parallel to the tape. The threading mechanism is trivial and takes up little space.

Ruggedness

In harsh environments differences will be found between transport designs. The helical scan transport is most sensitive as the large scanner has appreciable inertia and can generate large precessive forces and timing errors in a mobile or airborne environment. It is also the most critical on tape tension as variations cause changes in air film thickness and also result in changes in track angle which may cause interchange problems. Humidity changes can also affect the track angle in helical scan whereas transverse and stationary head recordings are unaffected.

Abstractions

When a helical scan recording is played at the wrong speed, parts of the track are recovered, allowing typically 40% of the data to be recovered. If, however, the tape speed is normal, but the scanner is driven at around twice the correct speed, then full data recovery is possible. Sync blocks will be recovered non-sequentially, and block addressing will be used to return the data to its correct sequence in memory. Error correction restores any sync blocks which are not recovered. This is the principle of the non-tracking (NT) rotary head recorder which clearly need no adjustment for interchange.

In principle an NT transport could play tapes having a variety of footprints provided the heads were of the appropriate azimuth angle and approximately the right width.

Non-Tracking is an attractive technology as instead of requiring increasing precision to allow narrower tracks, NT dispenses with the need for tracking altogether and, indeed depends upon severe mistracking to allow the sync blocks to be recovered in a statistical manner over several head sweeps. Thus an NT player can play tapes having a variety of track angles. If azimuth recording is used, tracks of various width can also be played. Following this argument further, it should be possible to play a stationary head multi-track recording using a NT helical scan transport. Provided the azimuth of the heads is appropriate, sync blocks can be recovered as the heads cross the tape tracks. Deflecting heads could be employed to increase the proportion of data recovered on each head sweep.

The converse argument is that, subject to details such as azimuth, a stationary head transport fitted with track following heads should in principle be able to play a helical scan tape by deflecting the heads at an appropriate speed to replicate the helical track angle. If several such heads are fitted, one can be resetting whilst another crosses the tape. This is a messy arrangement and is advanced only as an introduction to a better approach.

Magneto-optical readout has primarily been addressed to disk recording where the magneto-optic element is in the disk itself. It is, however possible to use magneto-optics to read conventional magnetic tape. This requires that the magneto-optic element is in the head. Briefly, a head is made having two poles and a narrow gap, but which is wide enough to span the entire width of the tape. A given track on the tape will cause the area of one of the poles above said track to follow the track magnetization. If polarized light is incident on the head pole, the reflected light will have that polarization rotated. A suitable analyzer can turn the rotation into an intensity variation which a sensor can detect. However, the sensor is a linear sensor which develops a one dimensional image of the cross-track magnetism. Any number or layout of tracks can be handled simply by sampling the cross track image at the appropriate points. If the sensor is, for example, a linear CCD element, the cross track image can be shifted out and analyzed in a software driven process. Thus track weave of a stationary head recording can be eliminated by shifting the sampling points in sympathy.

If, however, a helical scan recording is played, the slant tracks appear to continuously drift across the image. As one is lost at one edge of the head, another begins at the other edge. Again, subject to azimuth, it is possible to play a helical scan recording on a stationary head magneto-optic transport. Although the head is physical stationary, it has virtual movement by way of following the images of continuous slant tracks in the analysis process.

Thus in the limit, rotary head recorders can be made to play stationary head tapes and vice versa, suggesting that the techniques are not all that different. The rotary and stationary approaches are both complex as density rises, but the non-tracking principle may give the edge to the rotary transport in the future, with competition from magneto-optic replay in stationary head design.

To illustrate that nothing is new, in W.W.II a German fixed head audio tape recorder intended for dictation was fitted with a rotary playback head so that it could reproduce speech without pitch change over a wide range of linear tape speeds.

1. Watkinson, J.R. *The Art of Data Recording*, Chapters 7 and 8. Oxford: Focal Press (1994) ISBN 0 240 51309 6.