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ABSTRACT

The authors have developed a proto-type model of a Rotary-head Digital Audio Tape recorder (R-DAT) conforming to the specifications of the DAT conference. The proto-type model realizes a rapid access music search system, recording and playback capability of 48 KHz sampling rate 16 bits linear conversion, playback capability of 44.1 KHz, and reliability using sophisticated error correction algorithms.
This paper describes the signal processing and the performance of the R-DAT.

1. INTRODUCTION

Compact Disc(CD) players with only a playback function have been widely used as consumer use digital audio equipment. Moreover, a Digital Audio Tape recorder (DAT), which uses a small cassette as a recording medium, is expected to replace the conventional compact cassette tape recorder, and a DAT conference was formed in June, 1983 to establish its specifications.
About 80 domestic and overseas makers have discussed and examined a standard format for over 1 year, and the experimental specifications were decided upon in August, 1984.
At the DAT conference, reliability and exchangeability of the systems were examined, and the tentative improved standards both for a rotary head DAT (R-DAT) using the helical scanning method, and for a stationary head DAT (S-DAT) using the multi-track recording method, were agreed upon in July,1985.
The authors have developed a proto-type model R-DAT based on these standards, and this report describes its system design and signal processing.

2. OUTLINE OF R-DAT SYSTEM

The R-DAT system is highly regarded, not only for high quality

audio characteristics, but also for its small size, light weight, facility of use, and the many additional functions for which it can be used, giving applications from general audio to Hi-Fi audio.
Table 1 shows an outline of the system, Fig.1 shows the track format, and Fig.2 shows the block format.

Features of R-DAT are as follows.

(a) High recording density(129 $MBPI^2$) is obtained by a narrow track and guardbandless recording method.

(b) 30ϕmm drum diameter and 90° wrap angle are great advantages in making the equipment compact, permitting a rapid access music search system, keeping the tape in contact with the drum.

(c) System parameters are selected conforming to the three major sampling rates, currently used in the world : 48/44.1/32KHz.(44.1 KHz mode is used for playback only)

(d) After-recording of the PCM signal and the sub-code signal, one before or after the other, is possible by recording the PCM signal, sub-code signal, and ATF signal for tracking, on independent areas of a track.

(e) Many functions can be added by using the sub-code signals which have a capacity of 273 KBPS (about 4.6 times a CD sub-code capacity).

(f) The cassette is about half of the conventional compact cassette size, and can record 2 hours of information.

3. SYSTEM DESIGN AND SIGNAL PROCESSING

3-1 OUTLINE OF SYSTEM CONSTRUCTION

Fig.3 shows the system construction of a proto-type model.

The 2-channel audio signal is processed through a Low Pass Filter (LPF), Analog to Digital Converter, Encoder, and Modulator. Then an ATF signal is added, and the final signals are recorded on the tape through the Recording Amp, and rotary transformer.

In the playback mode, the reproduced signal from the head is processed through the Playback Amp, Equalizer, Signal Detector, Demodulator, Decoder, Digital to Analog Converter, LPF, and output as a 2-channel analog signal.

Memory is used for interleaving and companding the time base.
Servo block controls head tracking using reproduced ATF signal and revolution of both reel motor and drum motor.

System control circuit controls the system operation, time display, and rapid access music search system by using a microcomputer which uses output from the Envelope Detector, Key input, and sub-code information.
Fig.4 shows the clock relation of the system.

3-2 MODULATION, DEMODULATION

The modulation method for the system shoud have the following characteristics:

(a) The DC component should be excluded for recording and reproducing through the rotary transformer.

(b) Tmax/Tmin should be as small as possible for overwrite erasing.

(c) Tmax should be as small as possible for clock recovering.

As a method which has these characteristics, an 8-10 modulation method is employed in the R-DAT.
In this method, successive data bits are divided into groups of 8 bits, and each group is converted into 10 channel bits based on the algorithm so as to suppress the DC component, and Tmin and Tmax are 1 and 4 channel bits, respectively.
At demodulation, each channel data unit of 10 bits is converted into an 8-bit data unit through a conversion table.
Fig.5 shows the eye pattern of the reproduced signal modulated by this modulation method.

3-3 ERROR CONTROL METHOD

As an error correction method, this system employs the Doubly Encoded Reed Solomon Code, which has powerful error correction capabilities, and two-track completed interleaving, which has strong interpolating capabilities.

3-3-1 INTERLEAVING

As shown in Fig.6, the L and R channel data samples are divided into even samples and odd samples, and the data for one channel is disposed diagonally across the track.
By employing this interleaving, high reliability of reproduced data can be obtained, as either even or odd samples will be correct, even if all samples recorded in a track are lost by head clogging, or all samples recorded in the area between tape edge and center of tape are lost.

Fig.7 shows the memory construction, where, symbol means an 8-bit unit of data which is generated by dividing a sample of 16-bit data into upper and lower units. Lou is the symbol of the upper unit first sampled from the left channel, and Loℓ is the symbol of the lower unit first sampled from the left channel.

In the area for writing even samples of the left channel n of D(n) disposed at co-ordinates (i,j,k) is calculated by the equation given below.

$$n = \lfloor i/2 \rfloor \times 104 + ((k) \bmod 2) \times 52 + \lfloor k/2 \rfloor \times 2 + 4x \qquad (1)$$

Where i=0-27, j=0-12, k=0-3 and $\lfloor m \rfloor$ denotes the largest integer, which may not be exceeded.

The other three groups are stored in the same manner. P is the check symbol of C1 code and Q is the check symbol of C2 code.

The order in which data is read from the memory to record on the +Azimuth track is as follows:

Starting from j=0 in the i-k plane, the data is read from the k=0 position, then the k=1 position at i=0, then from the k=0 and k=1 positions at i=1, and so on in zig-zag fashion up the i-axis k=0 and k=1 position. After one pass of the i-axis in this fashion, another pass is made reading the k=2 and k=3 positions in the same zig-zag manner, until the +Azimuth section of the i-k plane is completed for j=0. This procedure is repeated for j=1 to j=31, and then the -Azimuth section is read in the same way.

3-3-2 CODE CONSTRUCTION

As shown in Fig.7, data recorded on a track consists of four i-j planes, and each plane is doubly encoded by C1 code and C2 code. C1 code is constructed by (32,28,5) Reed Solomon Code over $GF(2^8)$, and C2 code is constructed by (32,26,7) Reed Solomon Code over $GF(2^8)$.
The parity check matrix of C1 code H1 and the parity check matrix of C2 code H2 are shown below.

$$H1 = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 & \cdots & 1 & 1 & 1 \\ \alpha^{31} & \alpha^{30} & \alpha^{29} & & \alpha^{n} & & \alpha^{2} & \alpha & 1 \\ \alpha^{62} & \alpha^{60} & \alpha^{58} & & \alpha^{2n} & & \alpha^{4} & \alpha^{2} & 1 \\ \alpha^{93} & \alpha^{90} & \alpha^{87} & \cdots & \alpha^{3n} & \cdots & \alpha^{6} & \alpha^{3} & 1 \end{bmatrix} \qquad (2)$$

$$H2 = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 & \cdots & 1 & 1 & 1 \\ \alpha^{31} & \alpha^{30} & \alpha^{29} & & \alpha^{n} & & \alpha^{2} & \alpha & 1 \\ \alpha^{62} & \alpha^{60} & \alpha^{58} & & \alpha^{2n} & & \alpha^{4} & \alpha^{2} & 1 \\ \alpha^{93} & \alpha^{90} & \alpha^{87} & & \alpha^{3n} & & \alpha^{6} & \alpha^{3} & 1 \\ \alpha^{124} & \alpha^{120} & \alpha^{116} & & \alpha^{4n} & & \alpha^{8} & \alpha^{4} & 1 \\ \alpha^{155} & \alpha^{150} & \alpha^{145} & \cdots & \alpha^{5n} & \cdots & \alpha^{10} & \alpha^{5} & 1 \end{bmatrix} \qquad (3)$$

where α is the root of the primitive polynomial

$$X^8 + X^4 + X^3 + X^2 + 1$$

D(i,j) is a symbol disposed at the location (i,j) in a i-j plane. C1 code of the i-th column and C2 code of the j-th row in a plane are filled in the equations (4).

$$H1 \cdot \begin{bmatrix} D(i,\ 0) \\ D(i,\ 1) \\ D(i,\ 2) \\ \vdots \\ D(i,31) \end{bmatrix} = 0 \ , \qquad H2 \cdot \begin{bmatrix} D(\ 0,j) \\ D(\ 1,j) \\ D(\ 2,j) \\ \vdots \\ D(31,j) \end{bmatrix} = 0 \qquad (4)$$

3-3-3 DECODING ALGORITHM AND ITS PERFORMANCE

Generally, a decoding algorithm has several variations. The authors employ an algorithm which has correction capability stronger than that of a CD.
Fig.8 shows C1 decoding algorithm.
Fig.9 shows C2 decoding algorithm.
C1 decoder corrects up to two errors, and sets the C1 flag when over 2 errors occur.
C2 decoder corrects up to 6 erasures detected by C1 flags.

Performance is calculated as follows.

(1) C1 decoding

Probability of misdetection is given approximately by,

$$P1e \cong \frac{5}{32} A_5 (32) \binom{5}{3} \left(\frac{Ps}{255}\right)^3 (1-Ps)^{29} \qquad (5)$$

where Ps gives the symbol error rate.

Probability of detection is given approximately by,

$$P1f \cong \binom{32}{2} Ps^2 (1-Ps)^{30} \qquad (6)$$

$$P1t \cong \frac{3}{32} \binom{32}{3} Ps^3 (1-Ps)^{29} + \frac{2}{5} P1e \qquad (7)$$

where P1f is the probability of occurrence of correct symbol with C1 flag, and P1t is the probability of occurence of error symbol with C1 flag.

(2) C2 decoding

Probability of occurrence for mis-corrected sound is given approximately by,

$$P_M \cong \frac{7}{32} \left\{ A_7 \binom{7}{5} \left(\frac{P1t}{255}\right)^5 P1c^{27} \right.$$

$$\left. + \binom{32}{2} P1t^2 \binom{30}{4} P1f^4 \binom{26}{1} P1eP1c^{25} \right.$$

$$+ A_7(32)\binom{7}{2}\left(\frac{P1e}{255}\right)^2\binom{5}{1}P1t\binom{4}{3}(P1t+p1f)^3P1c^{26}\Big\} \qquad (8)$$

where $P1c = 1-P1t-P1f-P1e$

Probability of occurrence for compensated sound is also approximately given by,

$$P_X \cong \binom{32}{3}P1t^3\binom{29}{4}P1f^4P1c^{25}$$

$$+ \binom{32}{3}P1t^3\binom{29}{2}P1f^2\binom{27}{1}P1eP1c^{26}$$

$$+ \binom{32}{1}P1t\binom{31}{3}P1f^3\binom{29}{2}P1e^2P1c^{26}$$

$$+ \binom{32}{1}P1f\binom{31}{3}P1e^3P1c^{28} + \binom{32}{3}P1e^3P1c^{29} \qquad (9)$$

Fig.10 shows random error correction capability.
Fig.11 shows burst error correction capability.
Fig.12 shows the block error rate against the degree to which the head is off track.
Even if the tracking shift is up to 50%, the block error rate is only about $2x10^{-3}$ and correction was complete, with nocompensation for normal playback.

3-4 TRACKING METHOD

The tracking method of R-DAT is the ATF (Automatic Track Finding) method. The tracking error signal is generated from the difference of the crosstalk portions of the pilot signals which are recorded on the adjacent tracks on both sides, it controls the capstan motor rotation speed to bring tracking error close to zero. With this system,tracking error is within ± 3 um.

3-5 RAPID ACCESS MUSIC SEARCH

Rapid access music search can be done by reading the data for music search from the reproduced signal, while keeping the tape in contact with the drum and running at high speed. In this system the drum motor rotation speed and tape running speed are controlled so that the relative velocity between the rotary head and the tape is constant, and it is possible to find the music search data with the tape running at about 200 times normal speed.

3-5-1 DRUM REVOLUTION AT N TIMES NORMAL TAPE SPEED

Drum revolution is controlled as shown in Fig.13 which is calculated approximately by equations (10),(11).

Forward running direction

$$V_f \cong \frac{60}{R} (E + A \cdot N) \quad (r.p.m.) \qquad (10)$$

Reverse running direction

$$V_r \cong \frac{60}{R} (E - A \cdot N) \quad (r.p.m.) \qquad (11)$$

where R: Drum Diameter (mm)
E: Relative Velocity (mm/sec)
A: Tape Speed at Normal Play (mm/sec)

3-5-2 METHOD OF CONSTANT RELATIVE VELOCITY

When the head crosses the tracks, an envelope is produced. The number of envelopes within 90° can be calculated approximately by equation (12),(13).

Forward running direction

$$T_f \cong 7.5x10^3 \frac{A \cdot N}{V_f \cdot W} \qquad (12)$$

Reverse running direction

$$T_r \cong 7.5x10^3 \frac{A \cdot N}{V_r \cdot W} \qquad (13)$$

where W(mm) is the track pitch of tape running direction.

In this system, tape speed is controlled so that the difference between the number of envelopes detected by the envelope detector and the number of envelopes calculated by equation (11),(12) is zero. This control can be performed by using a micro-computer which is programmed to act as a servo.
Fig.14 shows the envelope produced within 90°, at about 120 times tape speed running in the forward direction.
Fig.15 shows the algorithm to achieve constant relative velocity.

Fig.16 shows the appearance of a proto-type model

4. CONCLUSION

To sum up, the authors have described the system design and signal processing of a proto-type model of the R-DAT.
R-DAT is far superior to the conventional compact cassette tape recorder, due to its highly advanced performance, multi-function

capabilities, easy operation, and its smaller cassette size. For these reasons, we expect that the R-DAT will be used not only for audio signal recording but also for data recording with a large size memory (DAT-RAM).
The authors believe that the R-DAT is destined to take a leading position in the field of a newly emerging digital audio equipment.

5. ACKNOWLEDGMENT

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Table 1 Outline of R-DAT system

Item		Contents
Tape Width	(mm)	3.81
Tape Speed	(mm/s)	8.150
Track Length	(mm)	23.501
Track Pitch	(μm)	13.591
Track Angle (Still)	(deg)	6°22′
Drum Diameter	(mm)	30
Drum Revolution Speed	(rpm)	2000
Writing Speed	(m/s)	3.134
Wrap Angle	(deg)	90.0
Number of Audio Channels		2
Sampling Frequency	(KHz)	48 44.1 (P.B. only) 32
Quantization	(bits)	16
Linear Recording Density	(KBPI)	61.0
Sub-code capacity	(KBPS)	273
Error Correcting Code		Doubly-Encoded RSC
Modulation Scheme		8-10
Tracking Method		ATF (area divided)
Cassette Size	(mm)	73×54×10.5

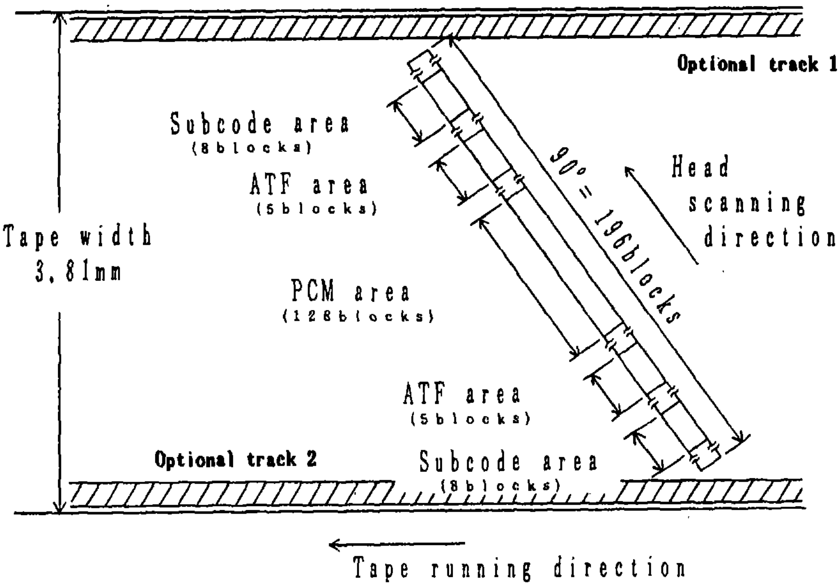


Fig. 1 Track format of R-DAT system

Sync 8 bits	Identify code 8 bits	Block address 8 bits	Parity 8 bits	Data (PCM data+parity) 256 bits (32 symbols)

← 288 bits (36 symbols) →

1 symbol = 8 bits

Parity = Identify code ⊕ Block address

⊕ : mod 2 addition

Fig. 2 Block format

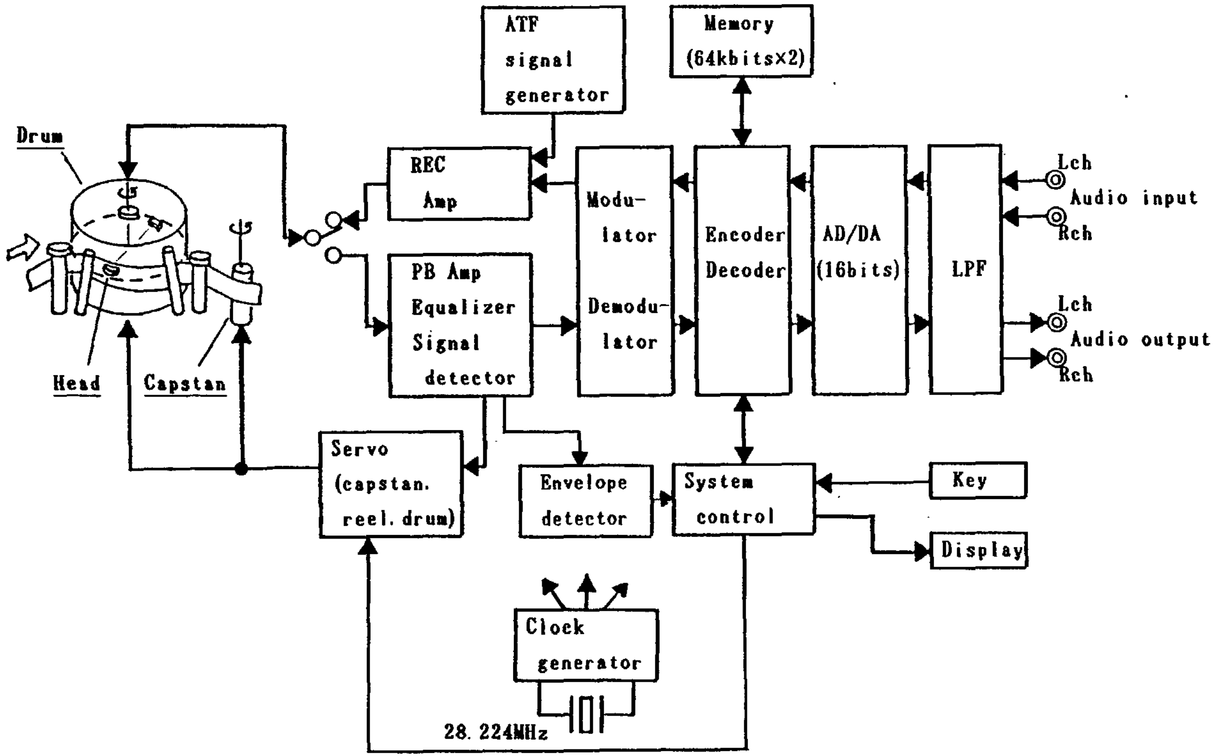
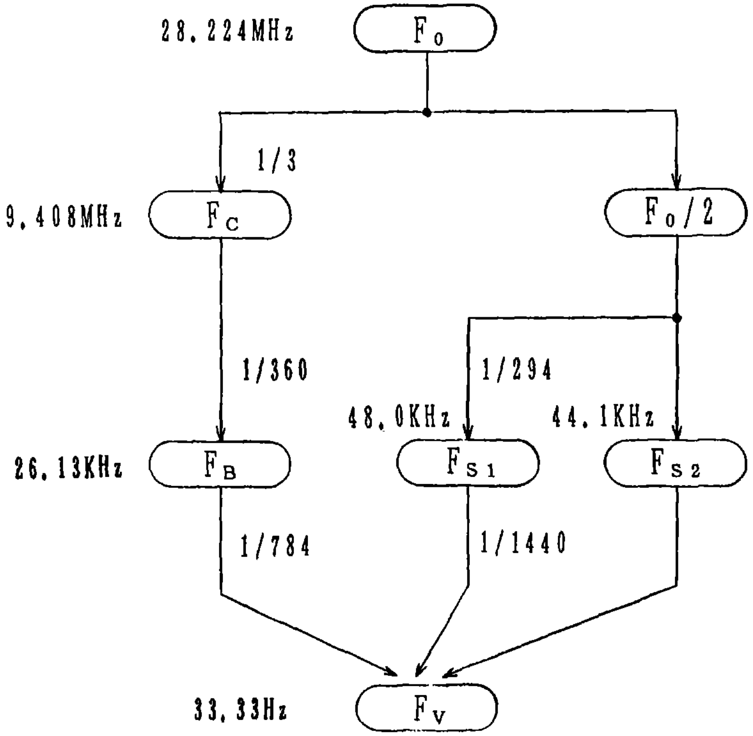
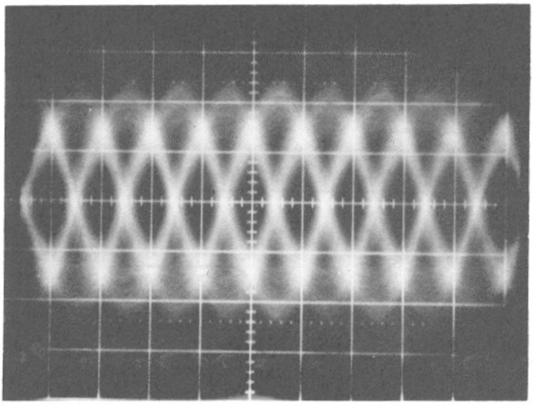


Fig. 3 Block diagram of R-DAT system



F_0 : Master clock
F_C : Channel clock
F_B : Block rate
F_V : Drum revolution rate
F_{S1}: Sampling rate
F_{S2}: Sampling rate

Fig. 4 Relation of clocks



Track pitch : 13.6μm
Head : Sendust
18μm
Tape : MP

⟶ 100ns/div

Fig. 5 Eye pattern

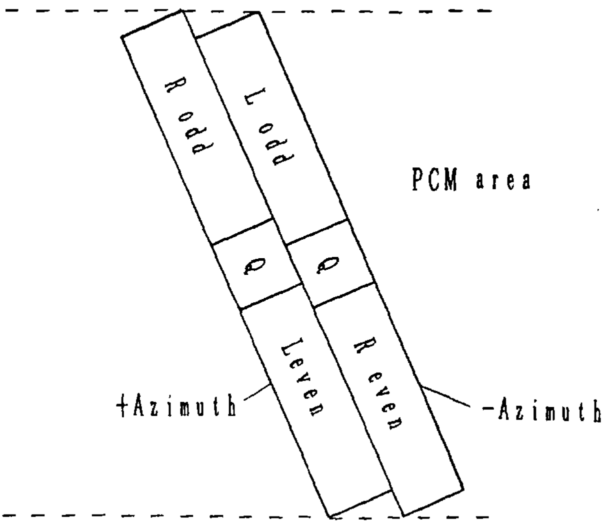


Fig. 6 Schematic representation of interleaving

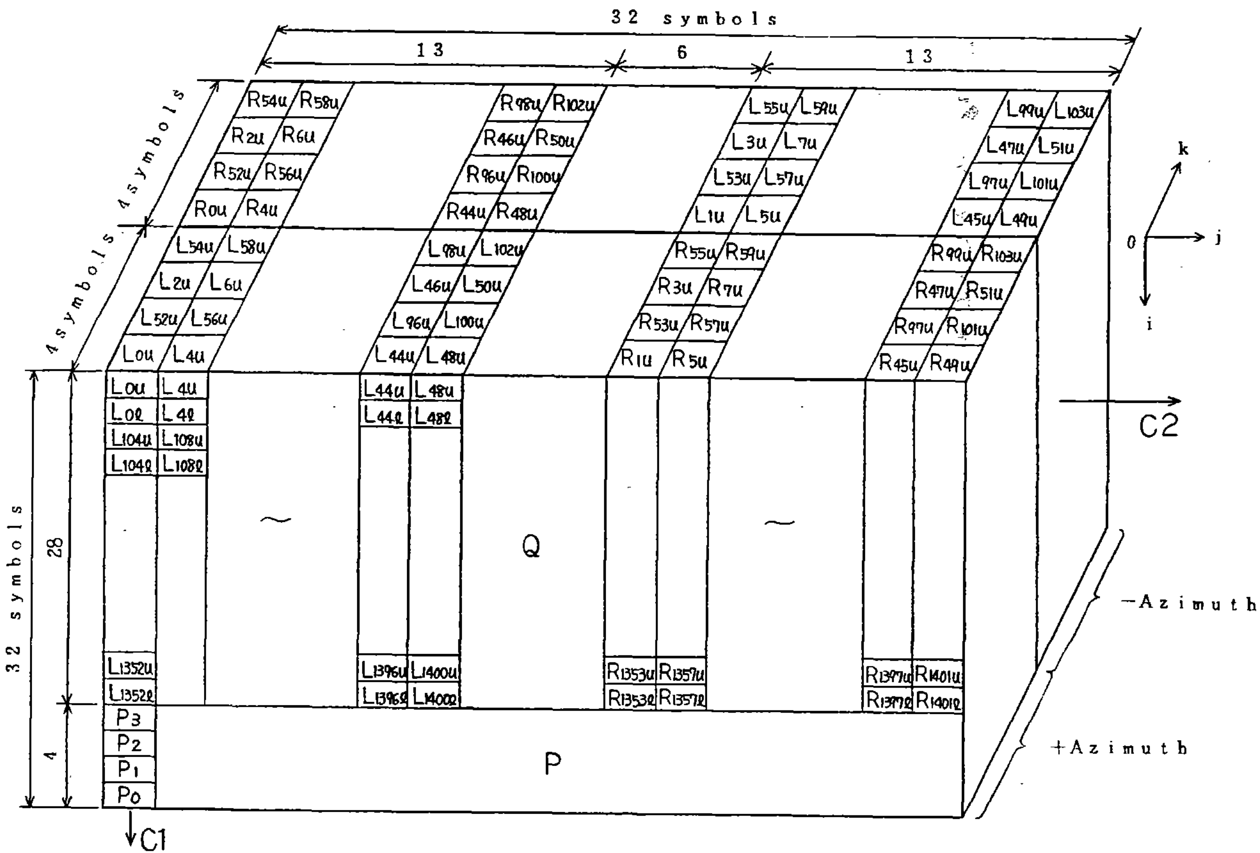
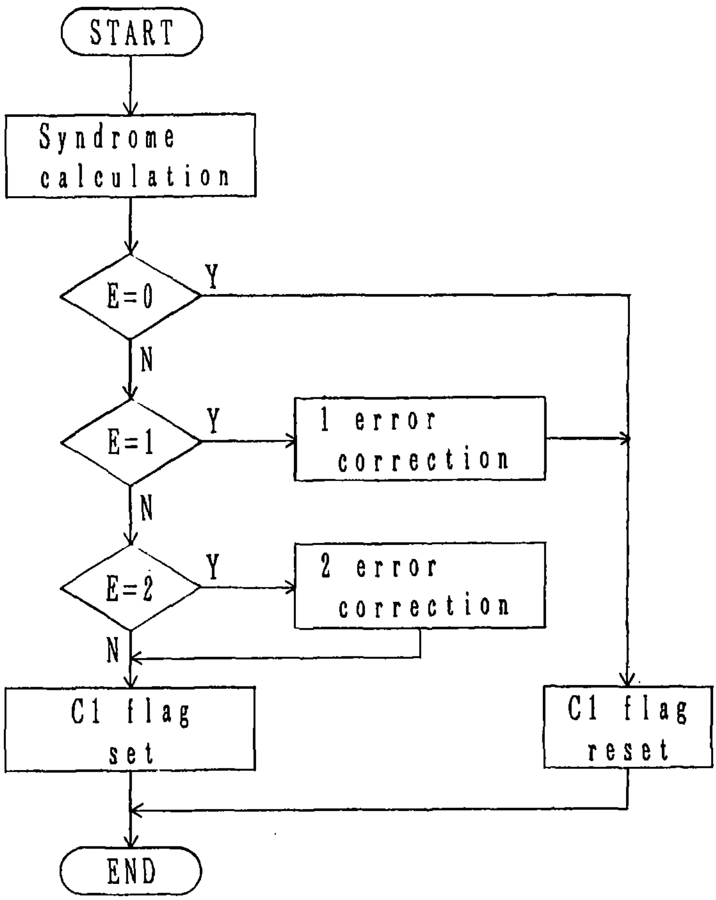
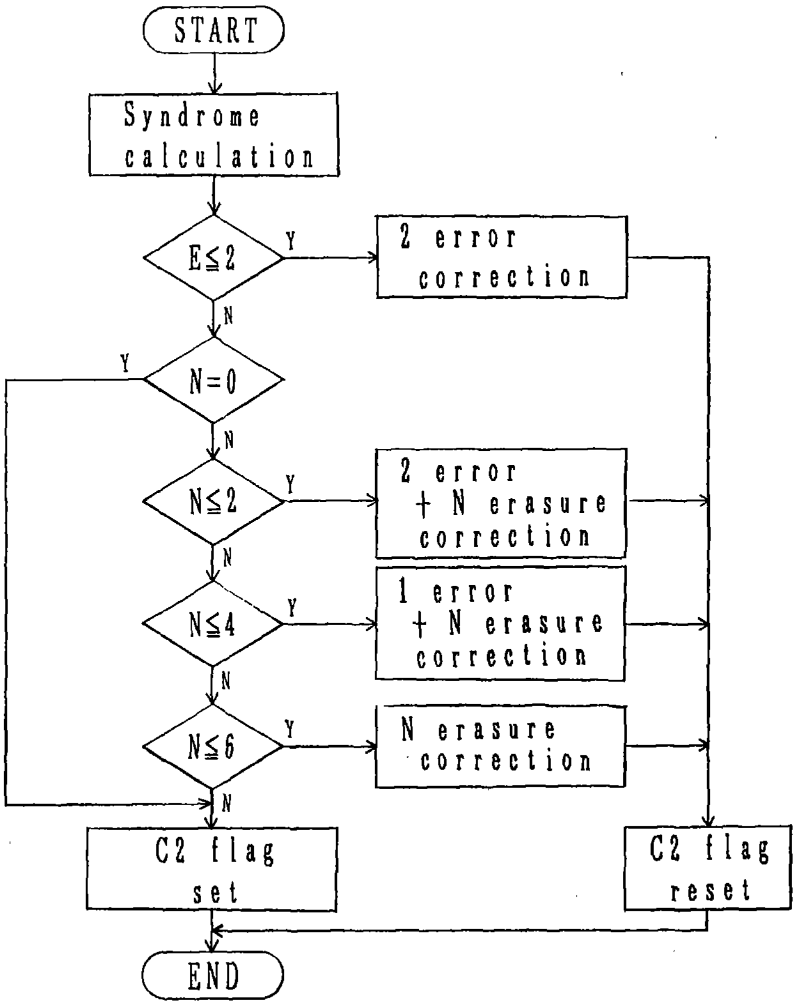


Fig. 7 Memory construction



where E : Number of errors.

Fig. 8 C1 decoding algorithm



where E : Number of errors
N : Number of C1 flags

Fig. 9 C2 decoding algorithm

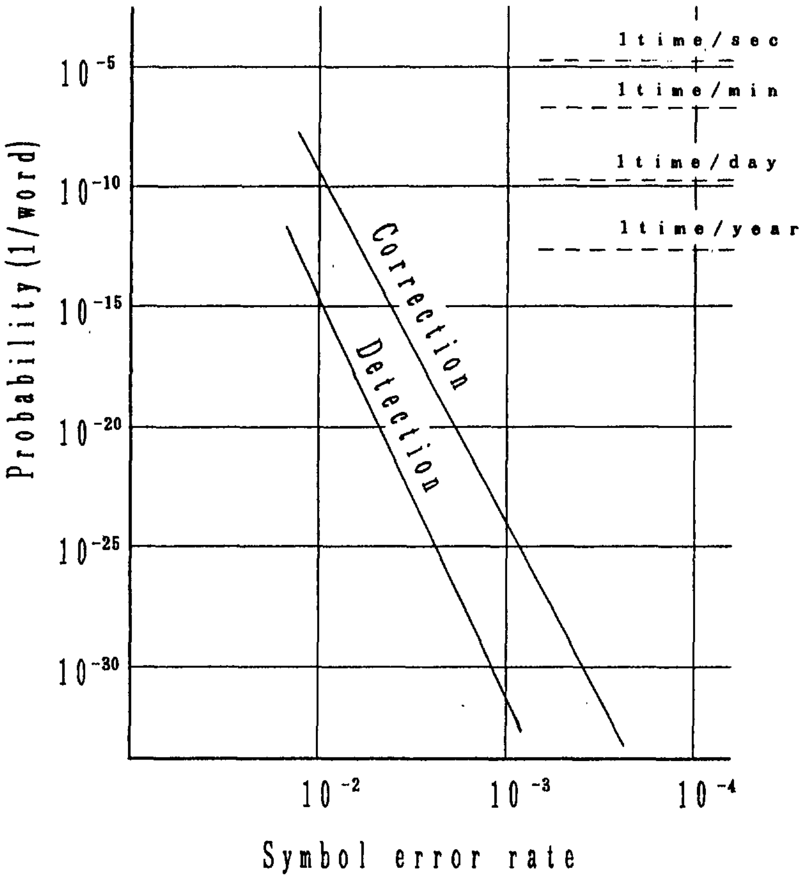


Fig. 10 Capability of random error correction

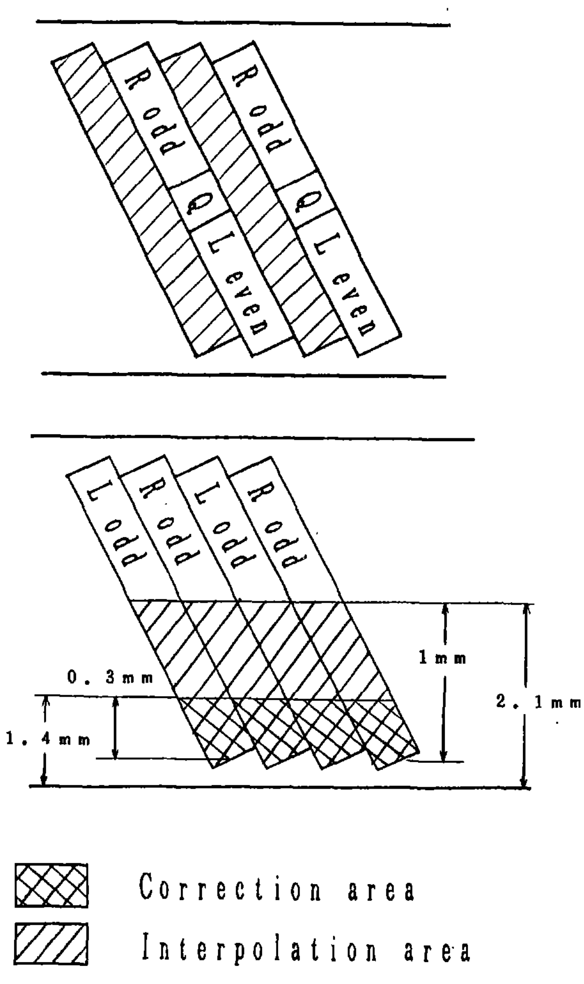


Fig. 11 Interpolation and correction capability for burst error

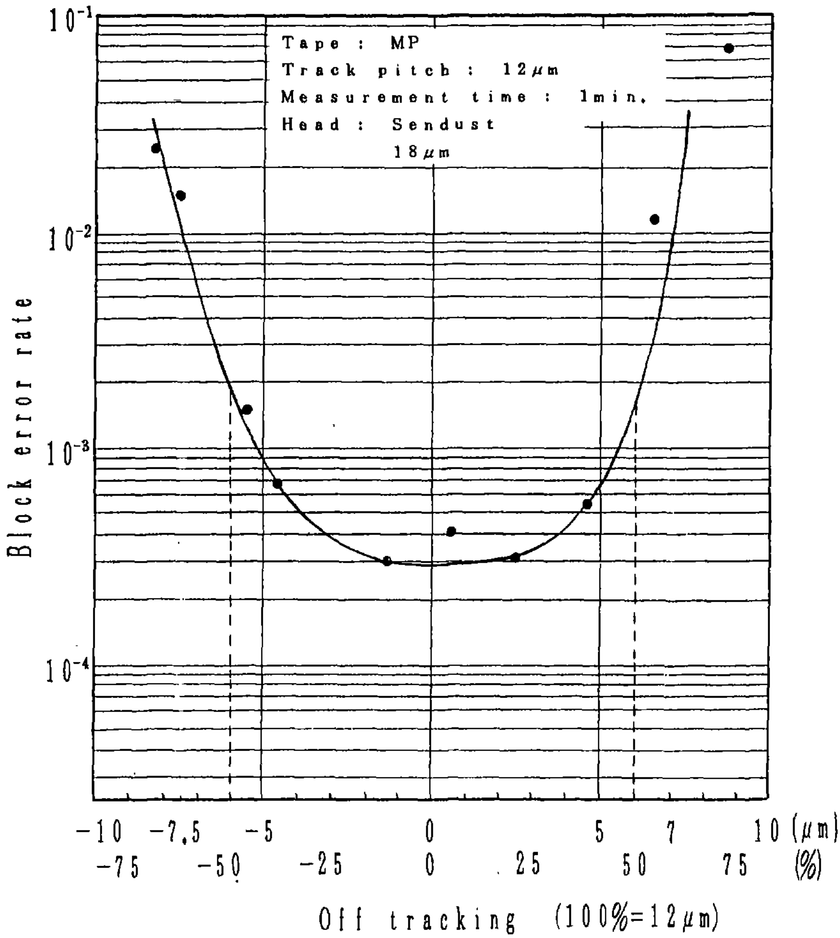


Fig. 12 Block error rate vs. off tracking

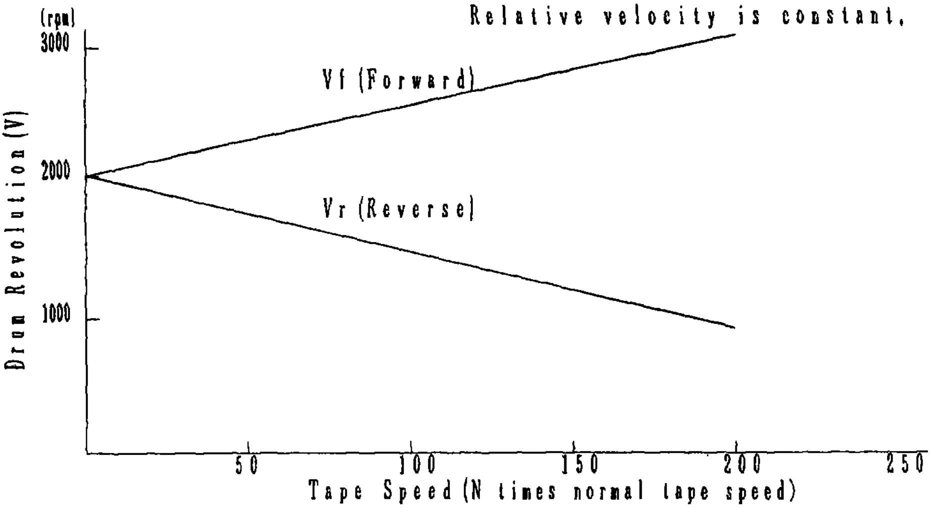


Fig. 13 Tape speed vs. drum revolution

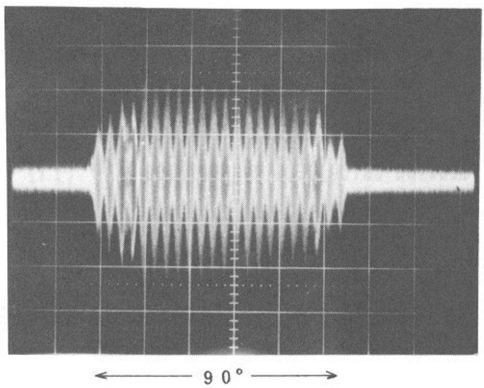
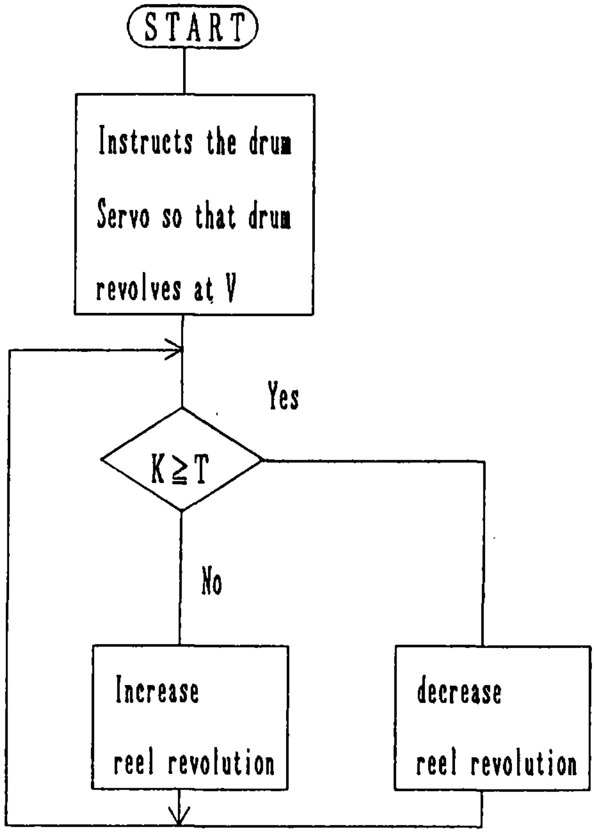


Fig. 14 Envelope at 120times speed



V:Drum revolution calculated by equation(10) (11)

K:Number of reproduced envelopes

T:Number of envelopes calculated by equation(12) (13)

Fig. 15 Algorithm for constant relative velocity

Fig. 16 Appearance of a proto-type model